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Doppler Sodar Measurement Of Wind Climatology Of Calgary

RMD Report 84/28

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DOPPLER SODAR MEASUREMENT OF WIND CLIMATOLOGY OF CALGARY

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DOPPLER SODAR MEASUREMENT OF
WIND CLIMATOLOGY OF CALGARY

by

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for

Research Management Division
Alberta Environment

RMD Report 84/28

1984

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ABSTRACT

A Doppler sodar was operated at Springbank Airport, near Calgary, from November 1980 until March 1983 to obtain data on winds above 75 m on a regular basis. The data for various levels up to 300 m were analysed for diurnal and seasonal variations, and compared with those obtained by conventional instruments near ground at Calgary International Airport, The University of Calgary Campus, and the Springbank Airport.

All stations exhibited a seasonal variation in which mean winds tended to be slightly stronger for six months of the year, centred on the month of March. Doppler winds showed a systematic increase with height, with the prevailing wind direction being W-WNW.

Vector-averaged mean wind at all heights measured by Doppler sodar was westerly and increased systematically with height from 2.0 m/s at 100 m to 7.0 m/s at 250 m, with a mean vertical gradient of wind speed of .04 s^{-1}. On average, the magnitude of the angular difference between winds at two levels depended linearly on the height difference between the two levels with a slope of 13°/100 m.

A common feature of the diurnal variation of average winds measured at all stations was a tendency for winds to be more northwesterly than average in the morning hours. A second feature was a weak counterflow in the early afternoon. This effect was present at all heights accessed by the Doppler sodar and may be due to anabatic/katabatic circulation.

Wind data during Chinook events showed a wide variation from event to event. Examination of a number of cases in detail showed that Arctic frontal movements, mountain lee waves, leeside cyclogenesis, and turbulent and radiative heat transfer are all important in the development of Chinooks.

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1. INTRODUCTION

1.1 GENERAL INTRODUCTION

Measurement of the wind profile in the first few hundred metres of the atmospheric boundary layer is important for various reasons. Knowledge of the wind profile is essential in understanding the dispersion of pollutants. It is also important in the siting of windpower generators. Regular measurements of wind speed and direction are routinely made using tower-mounted instruments. Heights of such towers are typically 10 m which is grossly inadequate to ascertain winds at higher levels. In the Chinook zone of southern Alberta, winds at a few hundred metres above the ground level could be quite different from surface winds. In addition, local perturbation of the mean wind field by hilly terrain makes it difficult to determine winds aloft by extrapolating measurements made at 10 m.

Routine measurement of winds to a height of hundreds of metres was impractical until recently, except at a few isolated places where tall towers exist. Knowledge of winds aloft has come from infrequent ascents of balloon-borne instruments. The development of Doppler sodars has made it possible to extend regular wind measurements to 300 m or more and to determine the variability of winds on a time scale much shorter than a day.

The atmospheric physics group at The University of Calgary has been studying the boundary layer using acoustic remote sensing techniques for several years. As part of its ongoing research programme, a Doppler sodar has been built and operated at the Springbank airport, 10 km to the west of Calgary. This report gives the results of regular measurements of winds aloft by this Doppler sodar since the end of 1980 November. These Doppler wind data were supplemented by additional meteorological data from both conventional instruments and acoustic remote sensing devices located at several sites in the Calgary region, as shown on the topographical map of Figure 1.

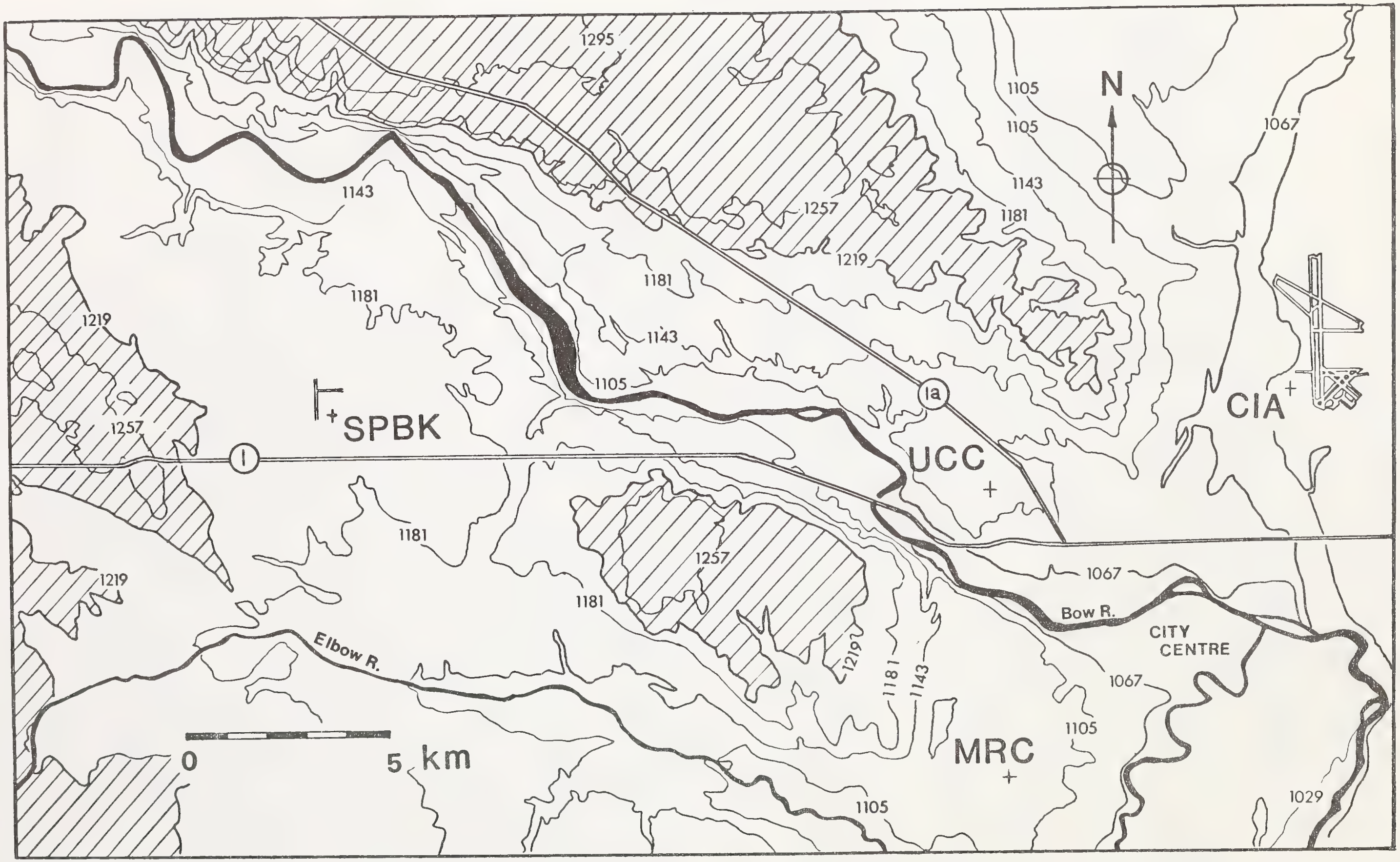


Figure 1. Topographical map of the Calgary region showing the data-gathering sites. Contours are shown at intervals of 38.1 m (125 ft). Terrain above the 1219 m (4000 ft) countour is shaded.

1.2 DOPPLER SODAR

Sodar is an acoustic "radar" device which is used to monitor turbulence and wind profiles in the atmospheric boundary layer. The technique upon which a sodar is based makes use of the ability of clear-air turbulence to scatter sound waves at large angles, although weakly. In a typical sodar system, short intense bursts of pure-tone sound are beamed upwards into the atmosphere, and backscattered signals are received by transducers located on the ground. The height of a scattering feature is determined from the time delay in arrival of the scattered sound (relative to the time of transmission), while the observed Doppler frequency shifts in the received signals are used to determine wind velocities at various heights. Brown and Hall (1978) have given an excellent review of acoustic methods of remote sensing in the atmosphere, including Doppler techniques. A more recent review may be found in Bourne (1982).

The first practical Doppler sodar system was developed almost a decade ago (Beran et al. 1974). Since then several variations of the system have been developed and used in atmospheric studies. A typical arrangement is shown in Figure 2. In recent years, commercially manufactured Doppler sodars have become available. A systematic comparison of Doppler sodar wind measurements with tower anemometers has been carried out (Kaimal, Baynton, and Gaynor, eds. 1980) in which it was found that Doppler sodars gave reliable measurements of winds aloft.

In a comparison of Doppler sodar with other wind measurement methods, certain aspects of the technique should be borne in mind. Doppler sodar data are averages in both space and time. Spatial averaging is imposed by the finite length of the tone burst and by the width of receiver beams. An individual wind estimate produced by the Doppler sodar must be thought of as an average over a volume of air having a typical dimension of 30 to 50 m. Time averaging is necessary because of the inherently "noisy" nature of sound backscattered from turbulence. Averaging over time scales varying from 10 to 60 minutes is imposed to

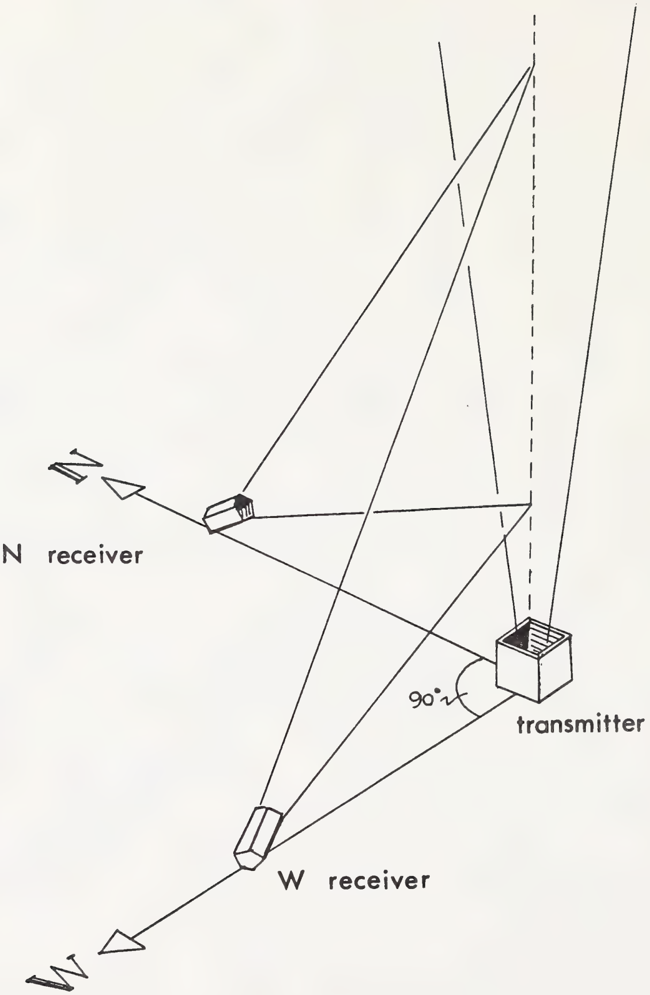


Figure 2. Geometery of a typical bistatic Doppler sodar viewed in perspective. An acoustic pulse is beamed vertically upward by a central transmitter. Inclined receivers on the ground determine the wind profile from the Doppler shift in the sound scattered out of the transmitter beam. Each receiver gives one component of the wind velocity.

reduce the variance of the Doppler wind estimates. Further, since the strength of echoes diminishes with height, the maximum height at which wind data can be retrieved corresponds roughly to the point where the received signals become buried in the local ambient acoustic background noise. Thus the working range of the instrument is subject to variation, and depends both on the state of the atmosphere (amount of backscatter) and on ambient background noise.

1.3 DIURNAL VARIATIONS IN WIND

Systematic departures from mean wind conditions may be expected at various times of day due to the diurnal cycle of solar heating. Longley (1968) has noted such a diurnal effect in long-term statistics of surface winds at Calgary, finding a tendency for southeasterly winds to occur in the afternoon hours. Thyer (1981) has observed a diurnal variation in summer-time upper wind data from twice-daily radiosondes over southern Alberta. Westerly flow present at all levels at 0500 MST changes to easterly flow having maximum near 500 m above ground level (AGL) at 1700 MST. Both authors attribute the easterly or southeasterly flow in the afternoon hours to anabatic/katabatic (i.e., upslope/downslope) circulation in the vicinity of the east slope of the Rocky Mountains. This phenomenon is akin to land-sea breeze circulation observed near oceans. Its effects are most pronounced in summer months when insolation is strongest.

1.4 WIND SHEAR

Wind shear is defined as a vertical gradient of vector wind velocity, and is manifested as differences in wind speed and/or directions at two heights. In the atmospheric boundary layer, provided thermal diffusion can be neglected, the presence of surface roughness in conjunction with atmospheric turbulence leads to a logarithmic dependence of the horizontal wind speed on height under equilibrium conditions. The Coriolis force causes the equilibrium horizontal wind to veer (i.e., rotate) with increasing height until it achieves the geostrophic wind direction about 1 km above the earth's surface. This is known as the Ekman spiral, and its realisation requires that the characteristic scale, or mixing length, of the turbulent eddies which are responsible for the vertical transport of momentum be small compared to the depth of the boundary layer. Under real conditions, the Ekman spiral is seldom observed. For example, when the atmosphere becomes unstable under the action of insolation, the convective circulation has a scale on the order of the depth of the boundary layer, and the angle between the near-surface wind and the geostrophic wind is smaller than that in the Ekman spiral. In the stable boundary layer, the mixing length is suitably small, but vertical momentum transfer can be inhibited at the upper boundary of strong surface inversion layers (typical depth 100 m to 200 m), and strong directional shears can result. Large shears are also observable across frontal surfaces such as those found in Chinooks.

1.5 SOUTHERN ALBERTA CHINOOKS

The Chinook is a fairly common phenomenon in southern Alberta during winter months. Previous analysis of large-scale meteorological data gathered during Chinooks (Brinkman 1969; Lester 1976) have shown that the warm, dry, gusty wind that blows down the eastern slopes of the Rockies is the result of several different processes which often interact. Arctic frontal movements, mountain lee waves, lee side cyclogenesis, and turbulent and radiative heat transfer are all important in the development of Chinooks. Because the processes operate on different scales, only some of which are regularly observed, the interactions of the associated phenomena are not well understood. Consequently, the question as to what constitutes a Chinook has been answered differently by different authors.

In order to choose a few Chinooks for detailed study, we have used a definition of a Chinook as a strong westerly flow characterised by a rise in temperature at ground level and strong winds from NW to SW directions. These characteristics do vary from one case to another. For example, in some cases there may be a gradual rise in temperature whereas in others a sudden rise occurs. The magnitude of the rise may also vary from case to case. Further, wind profiles may also behave differently from event to event (e.g., in some cases the Chinook winds may not reach the ground). In such cases it may not be possible to identify Chinooks by merely looking at the surface data. Hence, it is essential to obtain data on the upper level wind for the identification of Chinook conditions.

2. MATERIALS AND METHODS

2.1 INSTRUMENTATION

2.1.1 The Springbank Doppler Sodar

The Doppler sodar system developed and built at The University of Calgary was located at Springbank Airport (see Figure 1). This sodar became operational in November 1980. A plan view of the system is given in Figure 3. A transmit/receive array of nine acoustic transducers coupled to individual parabolic disk reflectors formed the central element of the system. The central array transmitted short upward bursts of 1600 Hz sound every 30 s. To reduce the sound level near the transmitter, the array was surrounded by a wall of straw bales 3.5 m high. The remaining elements of the system were four single-dish receivers located at 100 m and 200 m from the central array along two perpendicular baselines oriented roughly north and west. Each receiver was housed in its own acoustical enclosure to reduce sensitivity to ambient background noise. Specifications of the system are given in Table 1. For more details of the installation, see Leelananda (1981).

The mean wind velocity was extracted from the Doppler information in the received sound. The two horizontal lines (N-S and E-W) along which the single-dish receivers lay were taken as an x-y co-ordinate system (Figure 4). The sound received at any given instant of time has been scattered from a volume of air at mean elevation angle α. The observed Doppler shift (see Section 8.2) is given by

$$\Delta f = \frac{1}{2\pi} (\bar{k}_s - \bar{k}_o) \cdot \bar{v}$$

where $\bar{k}_o$ and $\bar{k}_s$ are the wave vectors of the incident and scattered waves, respectively. If Δf_x and Δf_y are frequency shifts measured at receivers along the two horizontal axes of the system, and Δf_z is the frequency shift measured at the central (vertical) receiver, then the components of wind velocity $\bar{v}$ at the scattering volume are given by

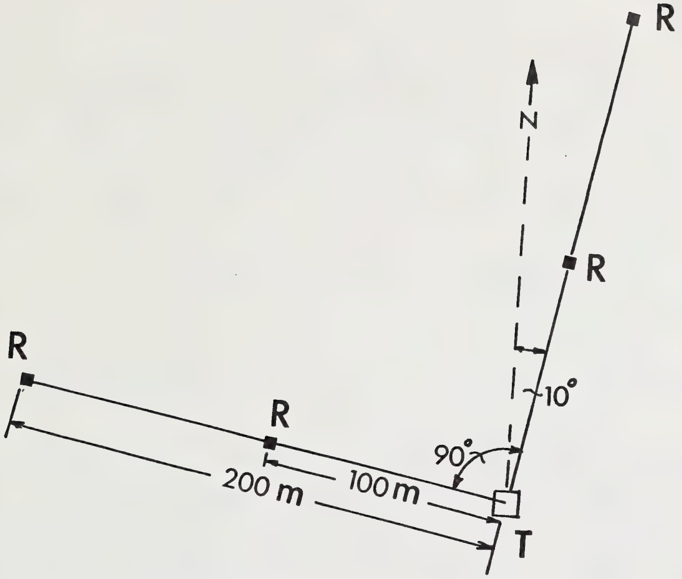


Figure 3. Plan view of Springbank Doppler sodar configuration (T = transmitter, R = receiver).

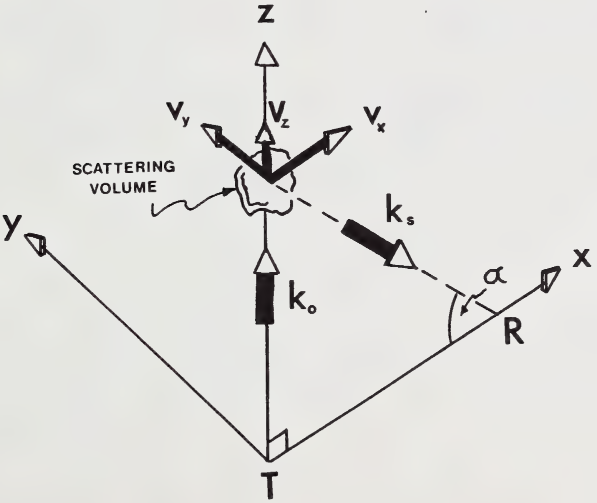


Figure 4. xyz co-ordinate system showing scattering volume, rectangular components of wind velocity vector (v_x,v_y,v_z), incident and scattered wave vectors (k_o,k_s), and the elevation angle of the received sound (α).

Table 1. Doppler sodar specifications.

Operating frequency	1600 Hz
Wavelength (0°C)	0.21 m
Input power (electrical)	~900 W
Output power (acoustical)	~100 W (est.)
Axis direction	10° E of N 280° E of N
Transmitter beam width	~4°
Receiver beam width	~12°
Minimum range	70 m
Maximum range	300 m
Range resolution	40 m
Pulse duration	240 ms
Repetition rate	2/minute
Receiver bandwidth	±80 Hz
Hetrodyned frequency	200 Hz
Digitisation frequency	800 Hz
Data reporting heights	100/150/200/250 m

$$v_z = - \frac{c}{2} \cdot \frac{\Delta f_z}{f}$$

$$v_y = \frac{c}{f \cos\alpha} [\Delta f_y + \Delta f_z (1 + \sin\alpha)]$$

$$v_x = \frac{c}{f \cos\alpha} [\Delta f_x + \Delta f_z (1 + \cos\alpha]$$

where c is the speed of sound and f is the output frequency (1600 Hz).

Estimates of v_x and v_y were made every 30 s, and averaged hourly by a microprocessor at the sounder site. In order to simplify the calculation of the horizontal wind, the linear terms in Δf_z were not included, as they tended to average to zero on a time scale of one hour. In addition, a mean speed of sound of 330 m/s was assumed. Since the surface temperature data were routinely recorded, the possibility of a post hoc correction to the wind data for the weak temperature dependence of c was retained, although not imposed on the archived data.

The sound from the transmitter was able to reach a given receiver by two paths, one scattered from the atmosphere above the transmitter and the other by direct surface transmission via the side lobes of the transmitting antenna. The directly transmitted sound pulse, of duration τ = 240 ms, was mixed with the scattered sound for vertical ranges below 65 m. As a result, a lower limit was imposed on the range of heights accessed by the sounder. The ideal vertical resolution Δz of the sodar was determined by the pulse duration according to

$$\Delta z \approx \frac{c\tau}{2}$$

In view of these ideal figures for minimum range and vertical resolution (65 m and 40 m, respectively), four height intervals centred at 100 m, 150 m, 200 m, and 250 m were selected for routine data reporting.

The above analysis was complicated by the effects of refraction (bending of ray paths) due to wind, and by the presence of background noise which led to errors in estimation of Δf_x and Δf_y. It has been determined that refraction effects can be neglected below 250 m (Leelananda and Mathews 1981). In addition, by rejecting noisy data, it was possible to reduce the statistical variance of the estimated Doppler shifts. Internal consistency of the hourly averaged Doppler data and comparison with surface sensors indicated an accuracy in individual hourly wind speed estimates of about 1 m/s and in direction of about 10° in azimuth.

2.1.2 Surface Instrumentation

Three basic instrumented sites (see Table 2) in the vicinity of the Doppler sodar installation routinely reported hourly surface meteorological data. Wind and temperature data from these sites have been compiled for the contract period (1980 October to 1983 March) to supplement the Doppler sodar wind data. The three sites (Calgary International Airport [CIA]; The University of Calgary Campus [UCC]; and Springbank Trailer [SPBK]) are shown on the map of Figure 1. This series of stations was separated by 8 km and 16 km on a roughly east-west axis. Other instrumented sites at Mount Royal College (MRC) in Calgary and at the Jumping Pound gas plant on the Copithorne Ridge west of Springbank Airport were considered for inclusion in this study. However, data reporting from these stations was spotty, and they were therefore excluded from the data archive.

At each site, the wind was measured by a cup anemometer and a wind vane mounted above the ground. The heights of the sensors were: CIA, 18.3 m; UCC and SPBK, 10 m (except for SPBK after 82-01-01, when a 5 m mast was substituted). Data were reported hourly. The wind speed was determined from the total number of rotations of the anemometer cup assembly in a given interval and was thus a scalar average speed. The speeds at CIA were reported in km/h, and were one-minute averages. At UCC and SPBK, winds were reported in m/s (1 m/s = 3.6 km/h 2 knots) and were one-hour averages. The direction of the wind vane was sampled every minute within the hour, and the prevailing (i.e., most frequent) direction was reported. Directions at CIA and UCC were reported with an

Table 2. Surface stations included in the study.[a]

Station No.	Site	Operating Agency	Elevation (ASL)	Mast Height	Wind Speed Units[d]	Angular Resolution for Wind Direction
1	Calgary International Airport (CIA)	Environment Canada	1074 m	18.3 m	km/h	22.5°
2	Univ. of Calgary Campus (UCC)	Univ. Calgary Dept. of Geography	1105 m	10 m	m/s	22.5°
3	Springbank Trailer (SPBK)	Univ. of Calgary Dept. of Physics	1196 m	10 m[b]	m/s	6°[c]

[a] All sites report 1. scalar averages of wind speed)
2. prevailing wind direction) on an hourly basis
3. point readings of temperature)

[b] 5 m after 82-01-01

[c] 22.5° prior to 81-06-01

[d] Minimum wind speed which will cause anemometer cups to rotate is 1 m/s

angular resolution of 22.5°; SPBK had 6° resolution. Temperatures were instantaneous readings on the hour in Celsius.

Three independent monostatic sodars, sited at CIA, MRC, and SPBK, were also operated during this study. Monostatic sodars produce facsimile chart records that can be interpreted to determine whether temperature inversions are present in the atmospheric boundary layer. In the present study they have provided supplementary data for case studies.

2.2 DATA ARCHIVE

Doppler wind data and surface wind and temperature records have been compiled for the period 1980 October to 1983 March and stored on digital magnetic tape. A complete description of the format of the data tape is given in Appendix 8.1. Coverage is schematically indicated in Figure 5 for the data types included in the archive.

2.3 METHOD OF ANALYSIS

Description of wind climatology of a given region approaches "completeness" only if data are available over many years. The relatively short (30 months) duration of this study has led us to concentrate on particular aspects of the wind climatology near Calgary. The availability of surface data from several stations permits the establishment of common trends and differences between spatially separated sites. Doppler data make it possible to extend this analysis in the vertical direction above the Springbank site.

The results of this study fall into two broad classes: statistical summaries of the available data and individual case studies of interesting events. We have analysed the data with regard to the following features:

1. monthly distributions of winds at various sites;
2. mean diurnal variation of winds;
3. monthly distributions of wind shears (differences in winds at two different heights);

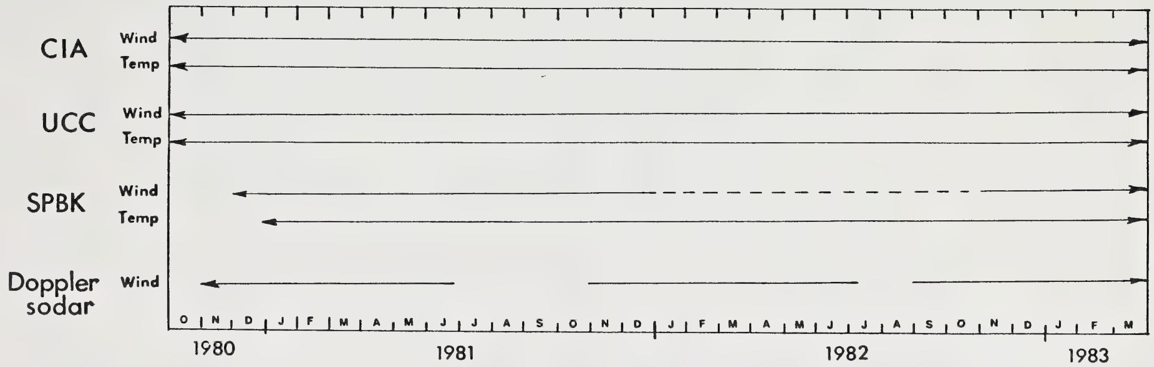


Figure 5. Data archive coverage. Solid horizontal lines indicate periods of substantially complete coverage for the data types indicated at the left of the figure. Gaps in the lines denote periods of sparse data. Dashed segement for SPBK wind data indicates where Transport Canada data were substituted (see Section 3.1).

4. case studies of effects in the diurnal variation of low-level winds; and
5. case studies of selected Chinook events.

Results of these analyses are presented in the following sections.

3. RESULTS

3.1 DATA COVERAGE

Table 3 gives the hours of data gathered for each month of the study period. The gap in SPBK surface wind data from 82-01-01 to 82-11-30 arose in connection with a changeover to new equipment at that site. Equipment on loan from The University of Calgary, Department of Geography, was replaced by a new anemometer, mast, and recording electronics. A problem with the new electronics caused light winds to be reported erroneously, while winds in excess of 5 m/s were correctly reported. Directions were not affected by this fault, which was corrected in 1982 November. Since Transport Canada operated a recording anemometer (mast height 10 m) in the Springbank Control Tower during this study, an alternative wind record existed. We have obtained the Transport Canada anemometer charts and have transcribed the data (speeds only) to complete the SPBK surface wind record.

Two major gaps appear in the Doppler sodar record, both attributable to modifications to the equipment. In the summer of 1981 the system was converted to the "complex covariance" method of frequency estimation (see Appendix 8.2). This conversion was motivated by expectations that the performance of the Doppler system in the presence of noise would be considerably improved. The improvement in performance was slight, however, and failed to lead to an increase in the working range of the sodar. Two months were likewise lost in 1982 in order to install on-line processing. This modification allowed the display of wind data in real time. Visual display of the wind profile made it possible to monitor system performance more closely, and led to increased system reliability.

For the remainder of the data gathering period (21 months, or 72% of the time following system installation), loss of data was caused mainly by power outages, snow or rain, and rejection of data values in periods of high background noise. During the months the system was operational it provided data for 85% of the possible hours, with no single month having less than 48% coverage (100 m level).

Table 3. Monthly hours of operation of wind sensors.

	Surface Stations			Doppler Heights			
	CIA	UCC	SPBK	100 m	150 m	200 m	250 m
1980 Oct	744	720	720	0	0	0	0
1980 Nov	720	720	642	337	332	321	231
1980 Dec	720	744	672	644	646	625	423
1981 Jan	744	724	661	589	591	578	462
1981 Feb	672	672	719	576	575	570	458
1981 Mar	744	712	649	666	666	645	488
1981 Apr	720	646	720	625	623	534	350
1981 May	744	742	730	478	468	383	248
1981 Jun	744	641	730	0	0	0	0
1981 Jul	720	744	720	0	0	0	0
1981 Aug	744	572	744	0	0	0	0
1981 Sep	720	666	514	0	0	0	0
1981 Oct	744	744	733	0	0	0	0
1981 Nov	720	695	0	70	70	70	70
1981 Dec	744	731	0	437	437	426	406
1982 Jan	744	723	0	717	717	717	717
1982 Feb	672	670	0	495	495	494	494
1982 Mar	744	744	0	391	391	391	387
1982 Apr	720	720	0	294	294	294	294
1982 May	744	733	0	343	343	343	342
1982 Jun	720	720	0	462	463	441	405
1982 Jul	744	668	0	10	9	6	2
1982 Aug	744	734	0	47	47	46	47
1982 Sep	720	696	0	561	560	563	557
1982 Oct	744	741	0	604	594	593	595
1982 Nov	720	720	699	660	671	672	670
1982 Dec	744	743	744	733	741	743	740
1983 Jan	744	736	714	706	712	713	711
1983 Feb	672	671	559	632	635	642	640
1983 Mar	744	292	491	427	435	442	439

3.2 SYSTEMATICS OF WIND DATA

3.2.1 Monthly Mean Values

Monthly means and standard deviations of hourly wind speed, together with directions of the mean vector wind, are given for surface level at different locations in Table 4 and for Doppler winds in Table 5. It should be noted that the mean wind speed is computed without reference to direction. The mean vector wind is computed by averaging rectangular components.

3.2.2 Directional Distribution

The data gathered during the entire period of study have been summarised in terms of distribution of hourly wind speed and directions for each month. These distributions are shown in the graphs given in Appendix 8.3. Directional distributions of Doppler winds are given in Appendix 8.4. In addition, Figures 6 and 7 show the distributions of wind directions produced when data for the entire period of the study were combined.

3.3 DIURNAL VARIATIONS

The presence of diurnal variation in Doppler wind data has been investigated by subtracting the long-term mean wind vector for a given height from hourly wind vectors at that height, then summing the wind differences of a 24-hour time base. For summations extending over several months, the effects of synoptic wind variations tend to cancel out, while 24-hour cycles are reinforced. Three winters (including the months from November to the following March) of uninterrupted Doppler data have been analysed in this way. For each winter period, a mean wind vector was calculated for each hour of the day. The overall mean wind for the given winter was then subtracted to yield twenty-four hourly difference vectors. These will be referred to as mean difference flow vectors, and are shown for 100 m and 200 m heights in Figure 8. In the absence of a true diurnal variation, the directions of the difference vectors should have been random. Instead, a coherent pattern emerged which

Table 4. Monthly summaries of surface winds.

	CIA		UCC		SPBK	
	Mean Speed Std. Dev. (m/s)	Dir.	Mean Speed Std. Dev. (m/s)	Dir.	Mean Speed Std. Dev. (m/s)	Dir.
1980 Oct	3.7 ± 2.9	291°	2.7 ± 1.5	340°	---	--
1980 Nov	4.5 ± 2.6	275°	2.8 ± 1.6	328°	---	--
1980 Dec	5.3 ± 2.9	283°	3.0 ± 1.9	326°	4.3 ± 2.9	269°
1981 Jan	3.6 ± 2.7	264°	2.7 ± 1.3	331°	3.2 ± 2.2	315°
1981 Feb	5.0 ± 2.9	276°	3.1 ± 1.9	323°	4.0 ± 2.9	290°
1981 Mar	4.9 ± 3.0	044°	3.1 ± 1.6	004°	3.5 ± 2.2	338°
1981 Apr	5.4 ± 3.0	262°	3.4 ± 2.0	307°	4.5 ± 3.0	274°
1981 May	5.1 ± 3.1	006°	3.1 ± 1.7	359°	3.9 ± 2.4	333°
1981 Jun	4.6 ± 2.5	298°	2.9 ± 1.5	333°	3.6 ± 2.2	302°
1981 Jul	4.4 ± 2.4	303°	2.6 ± 1.4	325°	3.2 ± 2.0	304°
1981 Aug	3.6 ± 1.8	122°	2.3 ± 1.2	330°	2.8 ± 1.9	323°
1981 Sep	4.0 ± 2.3	262°	2.5 ± 1.2	332°	2.9 ± 1.9	290°
1981 Oct	4.1 ± 2.3	275°	2.5 ± 1.5	333°	3.0 ± 2.1	301°
1981 Nov	4.2 ± 2.6	247°	2.4 ± 1.4	299°	2.9 ± 2.1	283°
1981 Dec	4.0 ± 2.8	257°	2.6 ± 1.7	285°	3.3 ± 2.4	296°
1982 Jan	4.8 ± 2.7	226°	2.6 ± 1.5	306°	---	--
1982 Feb	4.9 ± 2.7	344°	2.9 ± 1.7	314°	---	--
1982 Mar	4.0 ± 2.8	008°	2.7 ± 1.5	340°	---	--
1982 Apr	4.9 ± 3.0	276°	3.5 ± 1.9	285°	---	--
1982 May	4.6 ± 3.2	349°	3.2 ± 1.8	336°	---	--
1982 Jun	3.6 ± 2.8	005°	2.6 ± 1.3	320°	---	--
1982 Jul	3.8 ± 2.7	310°	2.5 ± 1.5	296°	---	--
1982 Aug	3.8 ± 2.4	267°	2.4 ± 1.3	293°	---	--
1982 Sep	3.9 ± 2.6	303°	2.5 ± 1.4	313°	---	--
1982 Oct	3.6 ± 2.8	263°	2.6 ± 1.7	291°	---	--
1982 Nov	3.1 ± 2.4	281°	2.3 ± 1.2	306°	4.3 ± 2.9	327°
1982 Dec	4.2 ± 3.0	269°	2.9 ± 1.9	290°	2.4 ± 2.0	300°
1983 Jan	3.6 ± 4.2	242°	2.6 ± 1.7	290°	2.4 ± 1.7	307°
1983 Feb	3.6 ± 2.7	186°	2.1 ± 1.1	272°	1.9 ± 1.4	326°
1983 Mar	4.3 ± 2.5	119°	2.6 ± 1.6	149°	2.6 ± 1.8	148°

Table 5. Monthly summaries of Doppler winds.

	100 m		150 m		200 m		250 m	
	Mean Speed Std. Dev. (m/s)	Dir.	Mean Speed Std. Dev. (m/s)	Dir.	Mean Speed Std. Dev. (m/s)	Dir.	Mean Speed Std. Dev. (m/s)	Dir.
1980 Oct	---		---		---		---	
1980 Nov	4.5 ± 2.9	286°	6.2 ± 3.8	260°	8.6 ± 5.4	268°	16.2 ± 7.5	289°
1980 Dec	4.0 ± 3.2	273°	6.6 ± 5.1	273°	8.9 ± 6.6	276°	14.1 ± 8.5	278°
1981 Jan	4.0 ± 2.4	300°	5.9 ± 3.8	288°	8.0 ± 5.1	287°	14.1 ± 7.0	292°
1981 Feb	4.6 ± 2.9	278°	7.7 ± 4.9	275°	10.1 ± 6.5	279°	13.0 ± 8.6	289°
1981 Mar	3.8 ± 2.0	309°	5.7 ± 3.2	297°	7.2 ± 4.1	301°	9.5 ± 5.8	308°
1981 Apr	4.8 ± 2.7	276°	7.3 ± 4.0	276°	9.5 ± 5.3	285°	12.3 ± 6.7	292°
1981 May	4.0 ± 2.1	339°	5.7 ± 3.2	335°	7.4 ± 4.3	332°	9.6 ± 5.5	340°
1981 Jun	---		---		---		---	
1981 Jul	---		---		---		---	
1981 Aug	---		---		---		---	
1981 Sep	---		---		---		---	
1981 Oct	---		---		---		---	
1981 Nov	---		---		---		---	
1981 Dec	3.8 ± 3.2	274°	6.3 ± 4.5	270°	8.4 ± 5.6	272°	10.8 ± 6.6	277°
1982 Jan	3.2 ± 2.6	291°	5.7 ± 4.6	288°	7.8 ± 5.7	288°	9.7 ± 6.4	289°
1982 Feb	3.6 ± 2.4	271°	6.2 ± 3.9	280°	8.0 ± 5.0	281°	9.6 ± 6.0	286°
1982 Mar	2.8 ± 1.9	261°	4.7 ± 2.8	240°	6.2 ± 3.7	252°	7.6 ± 4.5	273°

continued...

Table 5. Concluded.

	100 m		150 m		200 m		250 m	
	Mean Speed Std. Dev. (m/s)	Dir.	Mean Speed Std. Dev. (m/s)	Dir.	Mean Speed Std. Dev. (m/s)	Dir.	Mean Speed Std. Dev. (m/s)	Dir.
1982 Apr	5.1 ± 2.4	283°	7.7 ± 4.0	283°	9.8 ± 5.1°	285°	11.8 ± 6.1	286°
1982 May	4.4 ± 2.6	294°	6.5 ± 4.4	292°	8.7 ± 5.8	296°	11.4 ± 6.5	298°
1982 Jun	4.4 ± 2.8	303°	6.0 ± 3.6	307°	9.0 ± 6.3	306°	12.3 ± 7.8	306°
1982 Jul	---		---		---		---	
1982 Aug	---		---		---		---	
1982 Sep	4.5 ± 2.5	286°	6.8 ± 3.6	290°	9.0 ± 4.9	293°	10.3 ± 5.9	295°
1982 Oct	3.3 ± 2.2	274°	4.7 ± 3.1	275°	5.9 ± 4.0	280°	6.7 ± 4.6	283°
1982 Nov	3.0 ± 1.9	281°	4.7 ± 2.7	275°	6.1 ± 3,6	274°	7.2 ± 4.1	278°
1982 Dec	4.1 ± 1.9	281°	6.4 ± 3.1	278°	8.4 ± 3.9	277°	9.7 ± 4.4	280°
1983 Jan	3.3 ± 1.9	280°	5.3 ± 2.9	270°	6.8 ± 3.6	270°	7.8 ± 4.0	274°
1983 Feb	3.0 ± 1.9	269°	4.8 ± 2.9	262°	6.2 ± 3.8	266°	7.1 ± 4.4	271°
1983 Mar	2.7 ± 1.7	264°	4.1 ± 2.6	252°	5.3 ± 3.2	254°	5.9 ± 3.5	263°

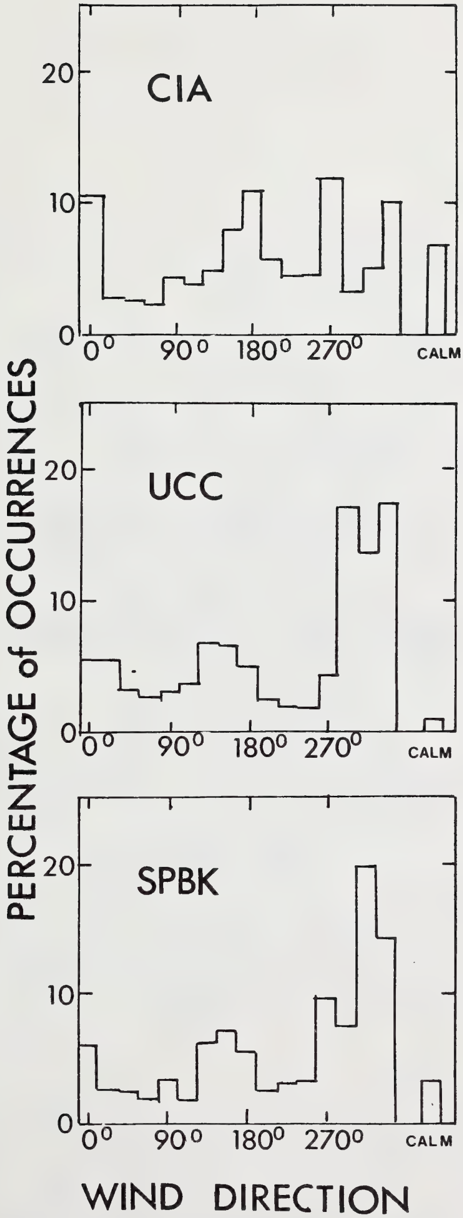


Figure 6. Distribution of hourly wind direction at surface stations for the whole period of the study. Directions are expressed as angles measured east of north. Vertical scales give percentages of total hours in which winds blew from the indicated directions.

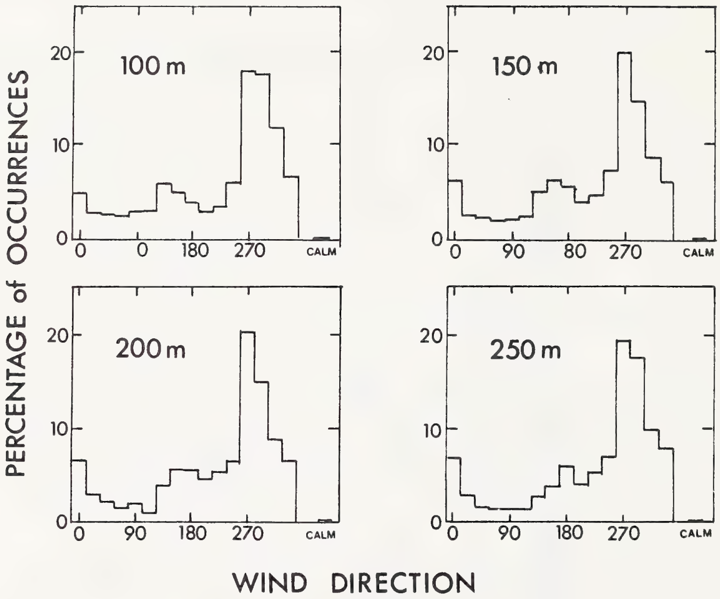


Figure 7. Distribution of hourly Doppler wind directions for the whole period of the study. Scales are the same as for Figure 6.

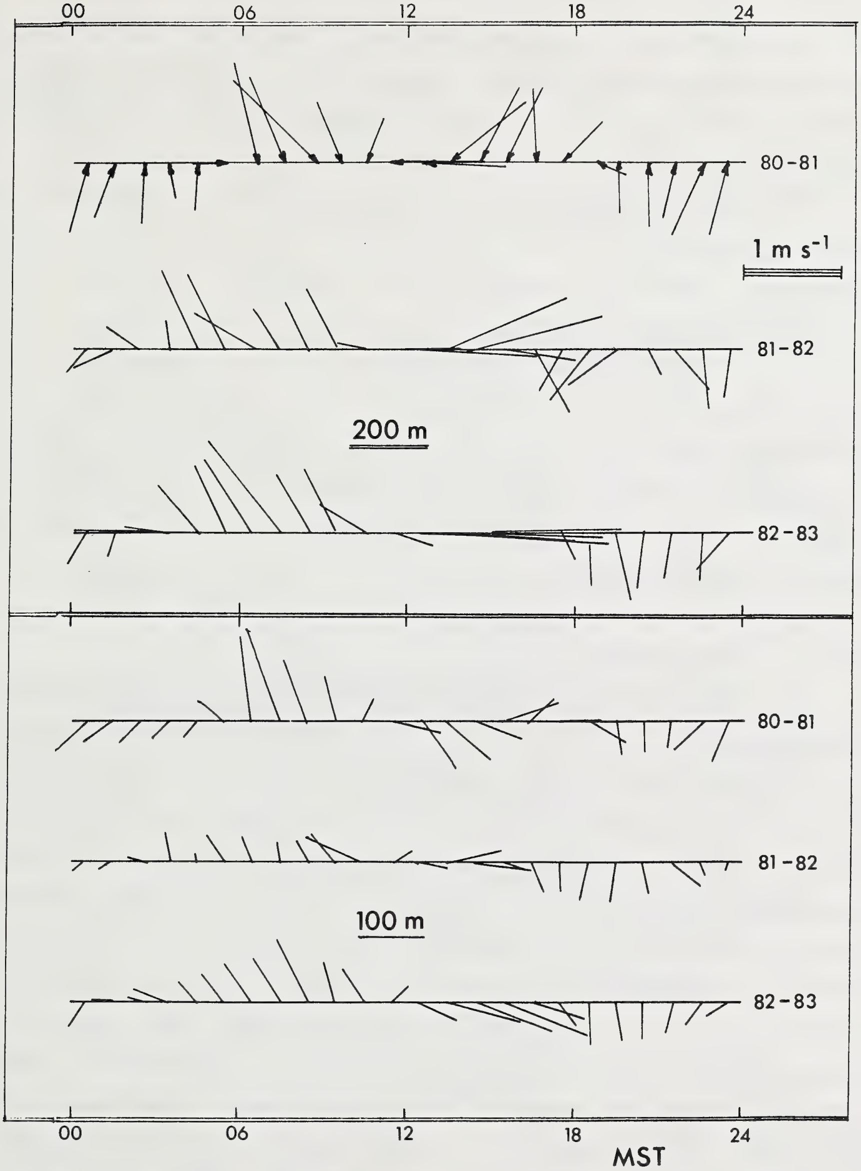


Figure 8. Mean diurnal variation of vector differences from the average wind. Vectors are drawn so that they terminate on the horizontal axis, as indicated by the arrowheads in the first row of data. Arrowheads have been omitted in the remaining rows for clarity. Results are shown for three winters at two Doppler heights to show systematically recurring features.

was reproduced in its gross features from winter to winter; the difference flow was oriented northwesterly in the morning hours (0400 to 1200 MST), had an easterly component in the afternoon (1200 to 1800 MST), shifting southerly overnight.

By considering three separate winters of Doppler data, then, it was possible to see recurring trends in the mean diurnal variation. When all periods were combined, the mean diurnal variation for the duration of this study (1980 October to 1983 March) resulted, as shown in Figure 9. Data are shown for all four Doppler heights, and also for the three surface stations. It is emphasized that the vectors displayed in Figure 9 are differences from the mean vector wind for each station or Doppler height. The appropriate mean vector is shown for comparison as a bold arrow beneath each diurnal plot.

3.4 WIND SHEAR

This section examines distributions of differences of hourly Doppler sodar winds in order to bring out mean features of the vertical wind profile observed at the Springbank site. No attempt was made to take differences of Doppler and surface winds because of the different averaging methods employed in the two data sets. Hourly wind vectors at 200 m and 100 m have been subtracted, and the distribution of magnitudes and directions of the resulting velocity differences are shown in Figure 10 for a typical month (1983 January). A third plot is included in the same figure to show the distribution of angular directional differences (absolute values) between the winds at the two heights. The mean velocity difference for this month has a magnitude of 3.8 m/s and a direction of 281°, reflecting the general westerly direction of elevated winds and their increase with height. Although some cases of large directional differences can occur, the mean angular difference between winds at the two levels is 21° for the month shown.

Table 6 gives corresponding monthly means for the whole period of the study. The overall mean velocity difference has a magnitude 4.5 m/s. The mean directional difference between 200 m

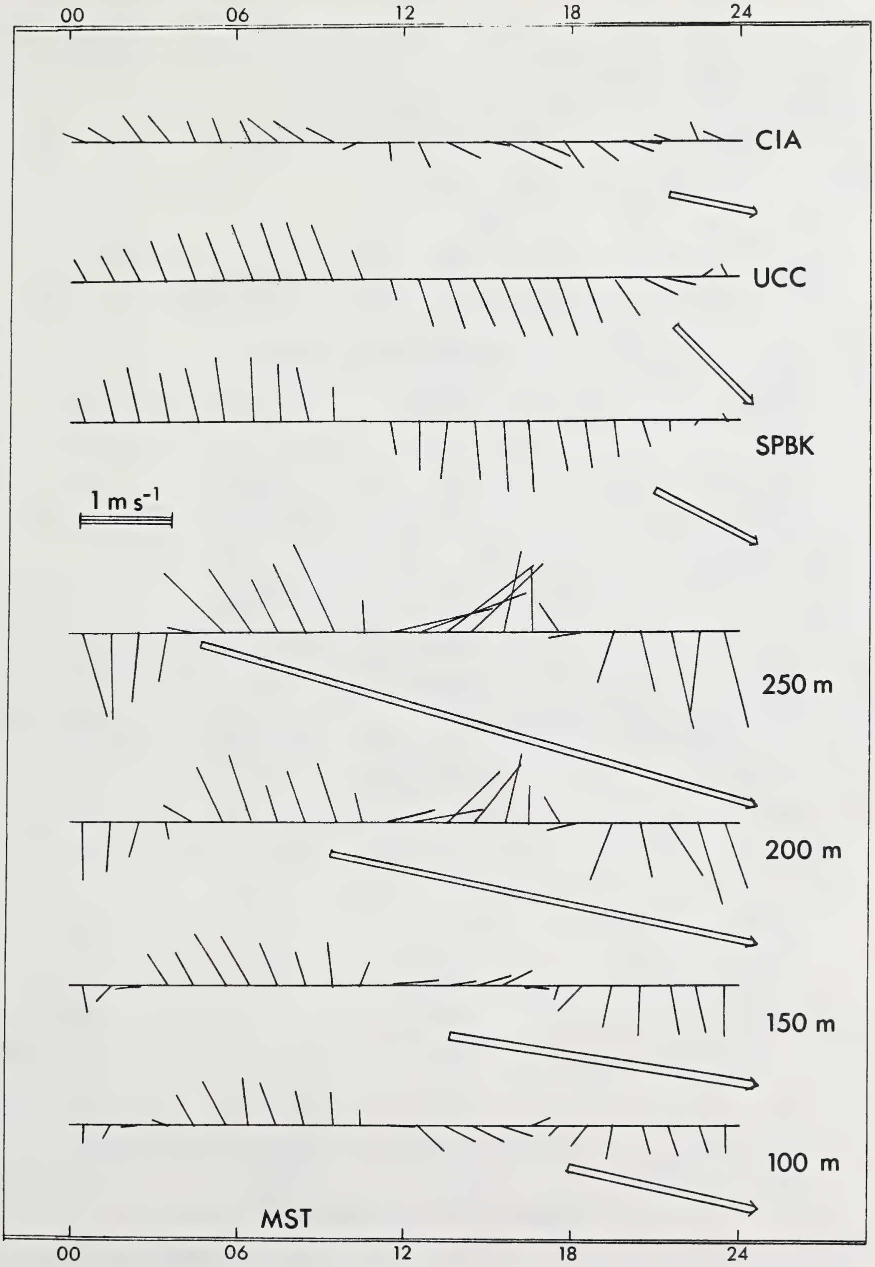


Figure 9. Whole-period mean diurnal variation of hourly winds at all stations and Doppler heights. Mean vector differences from the average wind (shown as a bold vector beneath each station) are plotted as in Figure 8.

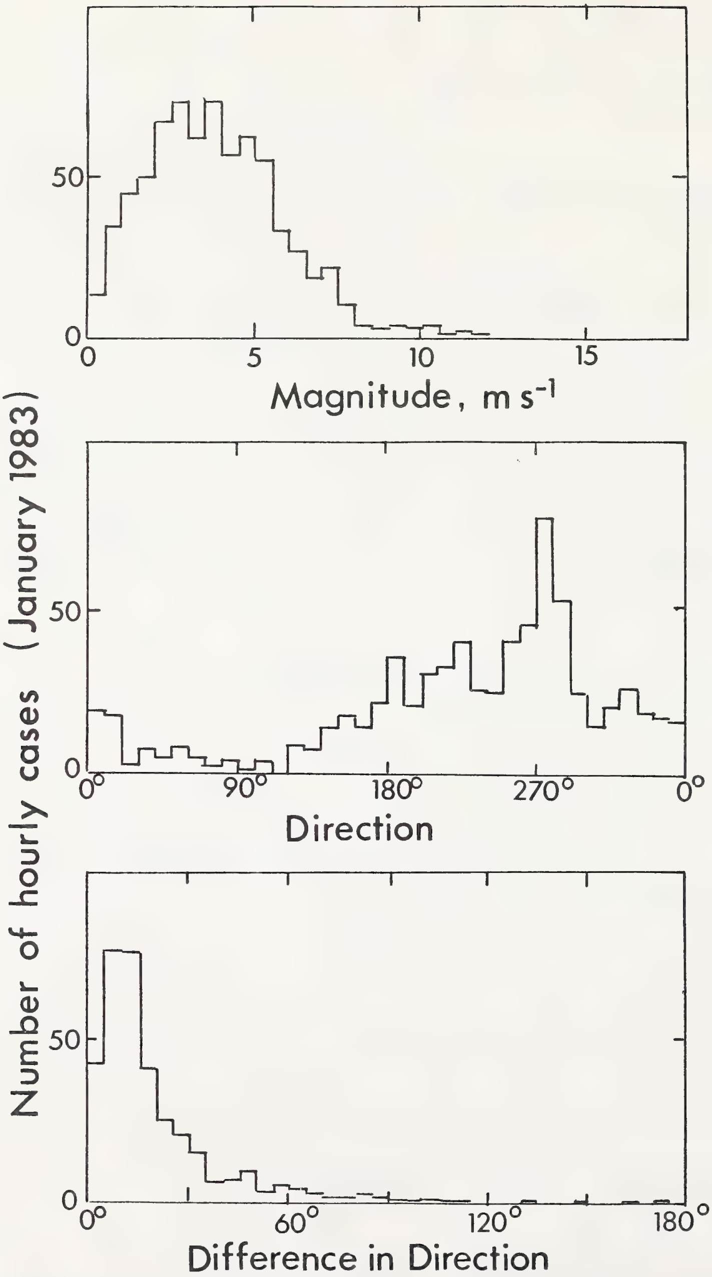


Figure 10. Distribution of hourly differences between the 200 m and 100 m Doppler winds for January 1983. The upper two plots give distributions of magnitudes and directions of hourly vector differences. The bottom plot gives distribution of angular difference in direction (absolute value) between the winds at the two heights.

Table 6. Monthly means of difference in winds at 200 m and 100 m.

Month	Mean Velocity Difference (magnitude)	Mean Velocity Difference (direction)	Mean Directional Difference
1980 Nov	5.2 m/s	248°	34°
1980 Dec	5.3 m/s	268°	21°
1981 Jan	4.6 m/s	270°	25°
1981 Feb	5.8 m/s	273°	16°
1981 Mar	4.0 m/s	275°	18°
1981 Apr	5.2 m/s	278°	14°
1981 May	3.9 m/s	280°	19°
1981 Dec	5.1 m/s	278°	24°
1982 Jan	5.2 m/s	280°	30°
1982 Feb	4.7 m/s	280°	19°
1982 Mar	3.7 m/s	279°	23°
1982 Apr	5.3 m/s	280°	17°
1982 May	5.2 m/s	281°	26°
1982 Jun	6.1 m/s	283°	34°
1982 Sep	4.9 m/s	284°	19°
1982 Oct	3.1 m/s	284°	20°
1982 Nov	3.5 m/s	283°	23°
1982 Dec	4.6 m/s	282°	17°
1983 Jan	3.8 m/s	281°	21°
1983 Feb	3.5 m/s	280°	21°
1983 Mar	2.8 m/s	279°	19°

and 100 m winds is 21°. Table 7 gives whole-period means for all possible pairs of Doppler heights.

3.5 CHINOOK EVENTS

Using the criteria discussed in Section 1.5, we have identified Chinook events which occurred during the three winters covered by the period of this study. These are listed in Appendix 8.5, which gives a brief summary of observations from Doppler wind data, surface data, and monostatic sodar facsimile records for each event. Monostatic sodar facsimile records have been found useful in identifying the descent of the interface between cold surface air and warm air aloft during Chinooks (Mathews and Hicks 1979). As the interface nears the ground, a descending echo layer appears on the facsimile record. A complete description of monostatic sodar records, including numerous examples, is given elsewhere (Mathews and Hicks 1977).

A number of individual Chinook events were selected from the first and last winters of the sudy for detailed analysis, and these are presented in Section 4.5.

Table 7. Whole period means of differences in winds at various pairs of Doppler heights.

Δz	z_1	z_2	Magnitude	Direction	Difference in Direction
50 m	150 m	100 m	2.6 m/s	270°	17°
	200 m	150 m	2.4 m/s	287°	13°
	250 m	200 m	3.1 m/s	299°	15°
100 m	200 m	100 m	4.5 m/s	279°	22°
	250 m	150 m	4.8 m/s	294°	21°
150 m	250 m	100 m	6.7 m/s	288°	27°

4. DISCUSSION

4.1 DOPPLER WIND COMPARISON

Testing of the validity of remotely-sensed Doppler wind data requires in situ sampling of a common air mass by instrumented towers or free/tethered balloons. Tests of Doppler sodars at the 300 m tower of the Boulder Atmospheric Observatory in Colorado have demonstrated excellent agreement between the two kinds of measurement (Kaimal, Baynton, and Gaynor 1980). In the present study, tower data were not available at SPBK and operation of a tethered balloon profiler was impossible so near to the airport runways. The validity of the Doppler data could only be inferred indirectly by comparison with surface winds at Springbank, and with twice-daily pilot balloon (pibal) data at 850 mb ($\sim$450 m AGL) taken at the Calgary International Airport. In making comparisons of this kind, it should be noted that:

1. The Doppler winds are hourly vector averages of wind velocity (sampled twice per minute).
2 The Springbank surface data are hourly scalar wind speed averages and prevailing wind directions (sampled every minute).
3. Except in well-mixed conditions, surface winds are often decoupled from the elevated flow.

For these reasons, absolute agreement among the various data sets cannot be expected. Correlations can, however, be demonstrated.

Surface winds and 100 m Doppler winds at Springbank were characterised by similar mean speeds of 4 m/s and standard deviations of $\sim$2.5 m/s (see Section 3.2). Differences of hourly values of these two variables exhibit a mean of 0.1 m/s and standard deviation 2.3 m/s, indicating a significant degree of correlation, although with considerable scatter. The small difference in mean speeds registered by the surface anemometer and the sodar at 100 m is somewhat surprising in view of the expected wind shear in the surface layer. Although the Doppler wind estimates were somewhat reduced relative to the anemometer data due to on-site vector averaging, it would appear that wind at 100 m may have been understimated by the sodar. Differences in surface and 100 m wind directions were occasionally large, but in 65% of the hourly observations the two directions lay in the same quadrant.

The correspondence of winds at various levels was expressed in terms of correlation coefficients of wind speeds and wind directions, as shown in Tables 8 and 9. Since the parent distributions of speed and direction were not normal in the statistical sense, a "non-parametric" rank correlation coefficient has been employed here. The number of hours included in these correlations was in excess of 2000 in every case, and the statistical errors in the correlation coefficients were of the order of 0.02. The correlation coefficient between surface winds and Doppler values was roughly 0.7, decreasing with increasing height. In comparison, correlation between Doppler winds at heights separated by 100 m averaged 0.86 for wind speed and 0.75 for wind direction. The highest values of correlation coefficients were observed between the 150 m and 250 m levels.

The above analysis shows that the Doppler data were self-consistent and were significantly correlated with surface winds. A further check was made by comparing the 250 m Doppler winds with pibal soundings at 850 mb for a 15-day period in December 1982. Although wind speed values showed no statistically significant correlation, directions agreed well (correlation coefficient 0.87), as indicated in Figure 11.

4.2 SYSTEMATICS OF DATA

4.2.1 Mean Monthly Values

Certain common features can be seen in the surface records. All stations exhibited a seasonal variation in which mean winds tended to be slightly stronger for the first six months of the year, January to June. At CIA, difference in mean winds for the two six-month periods was (0.8 ± 0.1) m/s; and at UCC, (0.3 ± 0.5) m/s, representing 10% to 15% of the mean wind speeds at these stations.

From Table 4 some differences can also be discerned

Table 8. Correlation coefficients of hourly wind speeds.

Height	100 m	150 m	200 m	250 m
Surface	0.72	0.69	0.64	0.53
100 m	--	0.89	0.87	0.81
150 m	--	--	0.96	0.86
200 m	--	--	--	0.91

Table 9. Correlation coefficients of hourly wind directions.

Height	100 m	150 m	200 m	250 m
Surface	0.69	0.67	0.62	0.57
100 m	--	0.78	0.74	0.72
150 m	--	--	0.90	0.77
200 m	--	--	--	0.83

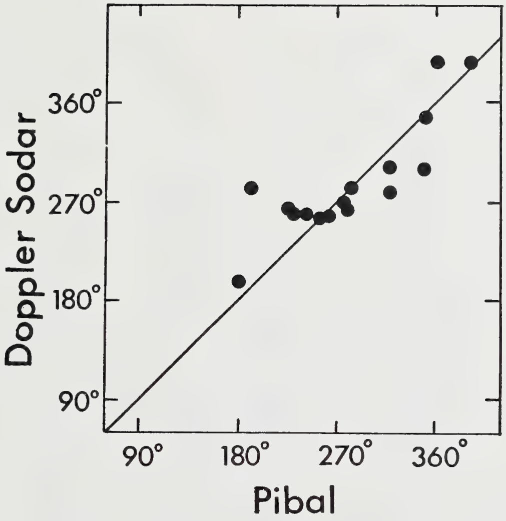


Figure 11. Comparison of directions of elevated winds determined by the Springbank Doppler sodar (250 m AGL) and pilot balloons at the Calgary International Airport (450 m AGL). Data are from October 1982. A line of unit slope is included as a reference. The correlation coefficient is 0.87.

among the surface stations. Mean wind speeds were systematically higher at CIA than at UCC and SPBK, an effect attributable to the higher mast at the CIA site. CIA wind directions showed more variability than for the other stations. Winds at UCC and SPBK tended to be more consistently from the NW quadrant than those at CIA. These directional effects may have been due to terrain or to the presence of structures near the CIA anemometer.

The mean wind at all heights measured by the Doppler sodar was westerly, being from a compass heading of 280°, and increased with height from 2.0 m/s at 100 m to 7.0 m/s at 250 m. These latter figures are magnitudes of vector-averaged winds; scalar means of wind speed (irrespective of direction) were somewhat larger, increasing from 3.5 m/s at 100 m to 9.9 m/s at 250 m.

The identification of seasonal trends in mean Doppler wind speeds was made difficult by the possibility that slight systematic effects may have been introduced by changes to the instrumentation in the summers of 1981 and 1982. However, Doppler wind directions were not likely to have been significantly biased by these instrumentation changes because they were derived from ratios of components. Monthly values of Doppler wind direction showed less variation throughout the year than did those for surface stations.

4.2.2 Directional Distribution

Distribution of wind directions at all stations, including Doppler winds at all heights, have a bimodal character, with westerly and southeasterly peaks present to a greater or lesser degree. The westerly peak is generally dominant, while the southeasterly peak is smaller and shows greater variability from month to month. Occurrences of light southeasterly winds in the presence of strong inversions are known to lead to adverse air pollution episodes in the Calgary urban area (e.g., Hicks and Mathews 1979). Tables 10 and 11 show monthly percentages of total hours in which winds blew from a generally southeasterly direction (azimuth angles 110° to 170°) and also from the westerly quadrant (213°to 327°) for all stations.

Table 10. Percentage of time wind flow has been observed from westerly (azimuth range 213° to 327°) and southeasterly (azimuth 110° to 170°) directions at Doppler levels.

	100 m		150 m		200 m		250 m	
	W	SE	W	SE	W	SE	W	SE
1980 Nov	72	4	60	10	68	6	85	2
1980 Dec	46	19	47	20	48	17	64	11
1981 Jan	51	10	49	11	47	9	43	5
1981 Feb	49	22	50	22	50	20	52	14
1981 Mar	40	27	39	28	40	26	41	16
1981 Apr	63	16	64	16	68	12	68	7
1981 May	36	16	38	15	37	11	34	8
1981 Dec	62	16	60	13	60	11	70	4
1982 Jan	54	14	54	11	54	8	58	6
1982 Feb	38	30	33	33	36	30	41	22
1982 Mar	32	26	32	24	35	22	43	13
1982 Apr	78	5	76	4	75	3	78	1
1982 May	54	12	57	9	56	7	57	6
1982 Jun	51	4	48	5	45	4	43	3
1982 Sep	57	6	54	8	54	9	54	7
1982 Oct	58	9	58	10	59	9	58	9
1982 Nov	67	11	62	11	63	9	64	8
1982 Dec	88	1	85	1	83	1	83	1
1983 Jan	68	11	64	11	65	8	68	7
1983 Feb	68	8	63	12	65	10	68	8
1983 Mar	49	14	48	13	48	13	50	13

Table 11. Percentage of hours surface winds were from westerly (azimuth 213° to 327°) and southeasterly (azimuth 110° to 170°) directions.

	CIA		UCC		SPBK	
	W	SE	W	SE	W	SE
1980 Oct	35	12	22	13	0	0
1980 Nov	48	7	34	4	0	0
1980 Dec	31	11	27	15	52	15
1981 Jan	30	12	24	7	50	10
1981 Feb	33	15	32	14	44	19
1981 Mar	20	24	14	24	26	26
1981 Apr	46	16	41	13	60	12
1981 May	23	17	21	17	35	15
1981 Jun	43	7	34	6	58	5
1981 Jul	37	15	29	9	50	16
1981 Aug	20	28	16	19	29	24
1981 Sep	29	18	17	18	44	20
1981 Oct	35	12	22	11	42	13
1981 Nov	38	13	48	13	55	10
1981 Dec	33	13	63	15	51	10
1982 Jan	17	19	39	23	0	0
1982 Feb	21	23	37	23	0	0
1982 Mar	19	19	39	24	0	0
1982 Apr	38	16	53	21	0	0
1982 May	19	23	39	24	0	0
1982 Jun	18	16	40	22	0	0
1982 Jul	31	13	52	16	0	0
1982 Aug	23	20	42	24	0	0
1982 Sep	22	12	44	21	0	0
1982 Oct	28	14	59	18	0	0
1982 Nov	23	12	57	15	32	8
1982 Dec	42	9	73	6	51	6
1983 Jan	25	13	60	14	43	14
1983 Feb	19	26	42	21	19	13
1983 Mar	12	34	28	32	22	35

4.3 DIURNAL VARIATION

A common feature of all diurnal plots (Figures 8 and 9) was a tendency for winds to be more northwesterly than the average in the morning hours. Surface stations showed a simple diurnal cycle in which this trend reversed following 1200 MST. (Diurnal variations at UCC and SPBK were smoother than at CIA due to the greater degree of averaging inherent in each hourly observation at the former stations. The Doppler diurnal vectors were "noisy" due to the large variance of individual estimates.) The afternoon trend was modified for the Doppler stations in a manner that increased with height, with the difference vectors being more northeasterly than for surface stations in the hours 1200 to 1800 MST.

These observed diurnal variations may have been the result of relatively small modulations of the westerly flow occurring at various times of day; alternatively, they may have been caused by enhanced occurrences of non-westerly winds at certain times. This latter interpretation is more in keeping with the results of Longley (1968) and Thyer (1981). To distinguish between these two alternatives and to bring out other details of the diurnal variation, it was necessary to examine the frequency with which winds blew from various directions as a function of time of day. These results are presented in Figure 12. Doppler winds at 100 m and 200 m have been classified into four quadrants centred on the N,E,S,W directions and the relative frequencies of wind directions in these quadrants, averaged over all available data, are plotted versus time of day. Figure 13 shows the corresponding diurnal variations in mean wind speed associated with each directional quadrant. Features of these plots may be summarised as follows:

1. W quadrant winds were predominant at all hours, being present 40% of the time with little dependence on time of day. The speed of westerly winds was considerably greater than for other quadrants, showing a peak from 1200 to 1800 MST.

2. E quadrant winds were relatively infrequent, with a marked increase in the early afternoon, corresponding to the easterly difference flows observed in the vector diurnal variation

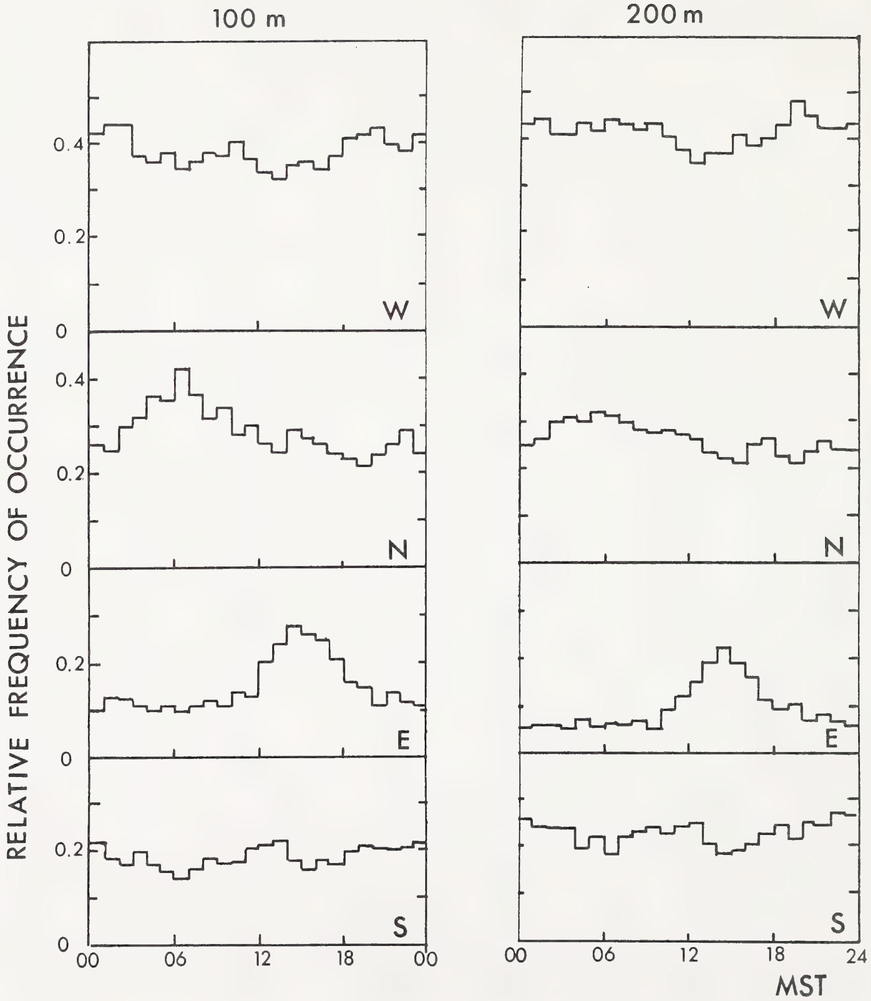


Figure 12. Diurnal variation of occurrences of Doppler winds from quadrants centred on cardinal compass points. Graphs on the left are for the 100 m height, those on the right for 200 m.

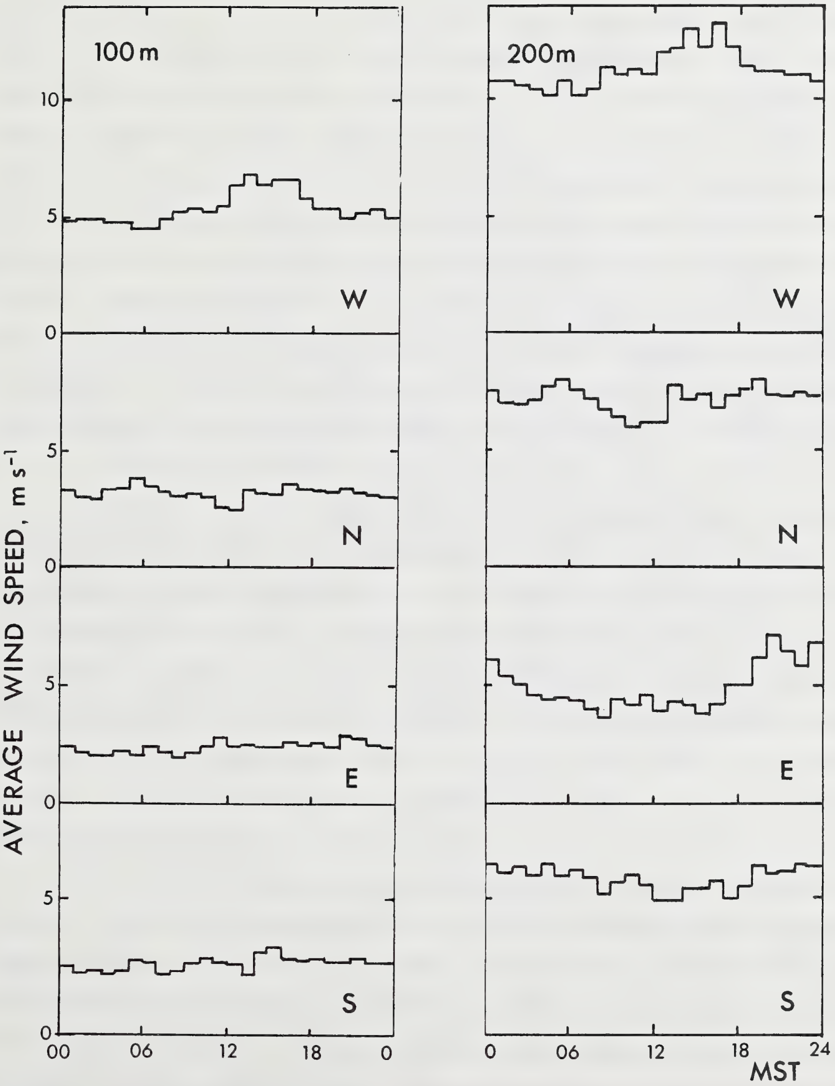


Figure 13. Diurnal variation of Doppler wind speeds associated with winds from the four cardinal quadrants.

of Figures 8 and 9. Wind speeds were light, showing a significant peak at 200 m from 1700 to 0100 MST.

3. N quadrant winds had a peak in frequency centred at 0600 MST, particularly for 100 m. N winds tended to be slightly weaker near midday than at other hours.

4. S quadrant winds showed little diurnal variation in this representation, and occurred with fairly uniform frequency at all times of day. A slight diurnal trend in wind speed is discernible at 250 m, similar to that shown by E winds.

The second feature above shows that a weak counter-flow can indeed be established in the early afternoon. This effect was present at all heights accessed by the Doppler sodar, and is in qualitative agreement with the observations of Longley and Thyer. The attribution of these effects to anabatic circulation is investigated in some detail in the case studies of Section 4.3.1.

4.3.1 Case Study of Diurnal Variation

Diurnal variation data show that light southeasterly winds can arise in the afternoon hours, possibly due to anabatic wind circulation. Examination of the diurnal variation of winds for the winter period of 1980-81 revealed that the month of March 1981 exhibited these trends more strongly than did other months. Several individual days from this month have been studied to reveal this behaviour in more detail. Attention was restricted to sunny days with no precipitation, and having enough heating during the day, sufficient radiation cooling during the night, and no snow on the ground, because these days should have been most likely to display anabatic diurnal circulation, which relies on differential heating of air parcels over mountains and plains. Doppler and surface wind data were supplemented by monostatic sodar facsimile chart records and synoptic meteorological maps. Six days were chosen for study (1981 March 8 to 12 and March 18), and all days showed a shifting of surface and near-surface winds into the easterly or southeasterly directions in the afternoon hours. Upper winds at the 500 mb level remained northwesterly, indicating that the easterly winds near the ground were produced by surface effects, and supporting the hypothesis that they were the result of anabatic flow. One case (that of 1981 March 11-12) was representative and is included here in some detail to show typical features of the observed circulation on these days.

Daytime hours of March 11 and 12 were clear and sunny with no precipitation and no snow on the ground. Bright sunshine for 8 and 9.5 hours respectively was reported for these days. However, a fair amount of snow was still present in the mountains.

Figure 14 shows the diurnal variations of wind speed and directions at various levels (ground, 100 m, and 200 m) for these days. The wind directions have been indicated by arrows. Diurnal variations of surface temperature have also been plotted in the same diagram. It can be seen that during the night and early morning of the March 11, winds at all levels had been N/NW. At 0200 MST, there was a sudden increase in wind speed at 200 m, and a further increase at both 100 m and 200 m at 0700 MST. By noon, winds became light and easterly. At about 1300 MST, winds at all levels became southeasterly and continued so until 0300 MST on March 12. At this time, winds up to 100 m changed to N/NW while the winds at 200 m were still southeasterly. Only at 0800 MST did the 200 m winds become northerly for about one hour before going to E/SE. At 0400 MST, March 13, the winds at 100 m level became N/NW; however, winds at 200 m were still E/SE. At 0600 MST winds at all levels became northwesterly.

The facsimile record for March 11 showed a shallow layer during the early morning hours, which deepened and became more turbulent during 0500 to 0800 MST. From 1100 to 1600 MST, thermal plumes rising to a maximum height of 200 m were observed. In the early evening hours, no echo was received; however, echoes suddenly appeared around 2000 MST. This corresponds to the time when an increase in wind speed was observed. By midnight, the surface layer had deepened to 300 m, becoming shallow again at 0200 MST with corresponding light winds. The elevated structure observed on the facsimile record of 81-03-12 between 0300 and 0600 MST might have

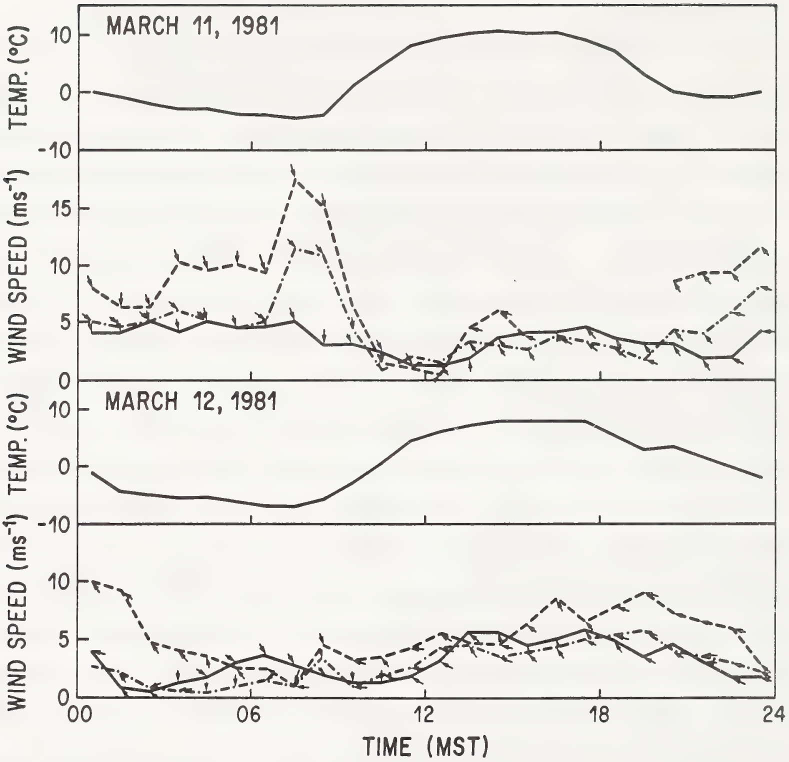


Figure 14. Temperature and wind records at Springbank for 1981 March 11 and 12. Wind directions are indicated by arrows. Winds are shown at three heights: solid curve, 10 m; dot-dash curve, 100m; dashed curve, 200 m.

been formed as a result of a wind shear as can be visualised from different wind directions at 100 m and 200 m levels. By 0700 MST, only a surface based shallow (100 m deep) layer was observed. At 1100 MST the surface layer was replaced by thermal plumes.

The 500 mb height contours have also been examined, and these show that the geostrophic wind was NW/NNW during the period under discussion.

These observations indicate a clear case of a diurnal shifting of winds which was confined to a shallow layer (100 m) near the ground, corresponding to the depth of the surface inversion layer evident on monostatic sodar facsimile records. Anabatic/katabatic circulation in the vicinity of the Rocky Mountains of Colorado has been observed by Hahn (1981), again with the mountain-influenced winds confined to the surface inversion layer. The occurrence of a similar phenomenon at Calgary is suggested by the case studies of March 1981.

4.4 WIND SHEAR

Observations of wind profiles in the boundary layer (Holton 1979, p.111) suggest that the wind speed substantially achieves the geostrophic value at a height of 500 m AGL. For a typical geostrophic wind speed value of 15 m/s, the average vertical gradient of wind speed in the height interval 100 m to 250 m is about .02 s^{-1}. From the Doppler wind data of Table 7, it is evident that the typical wind speed gradient observed in the present study is about a factor of two larger than this. An average shear of about .04 s^{-1} is indicated by Figure 15, in which the average observed wind speed difference is plotted against the height difference between pairs of Doppler levels. Since the Doppler data were essentially unverified by in situ measurements, it remains to be determined whether this large shear value was real or somehow an artefact of the Doppler calibration.

Directional differences in mean vector winds at various heights were small (less than 1° in azimuth). However, when absolute values of directional differences were averaged and plotted

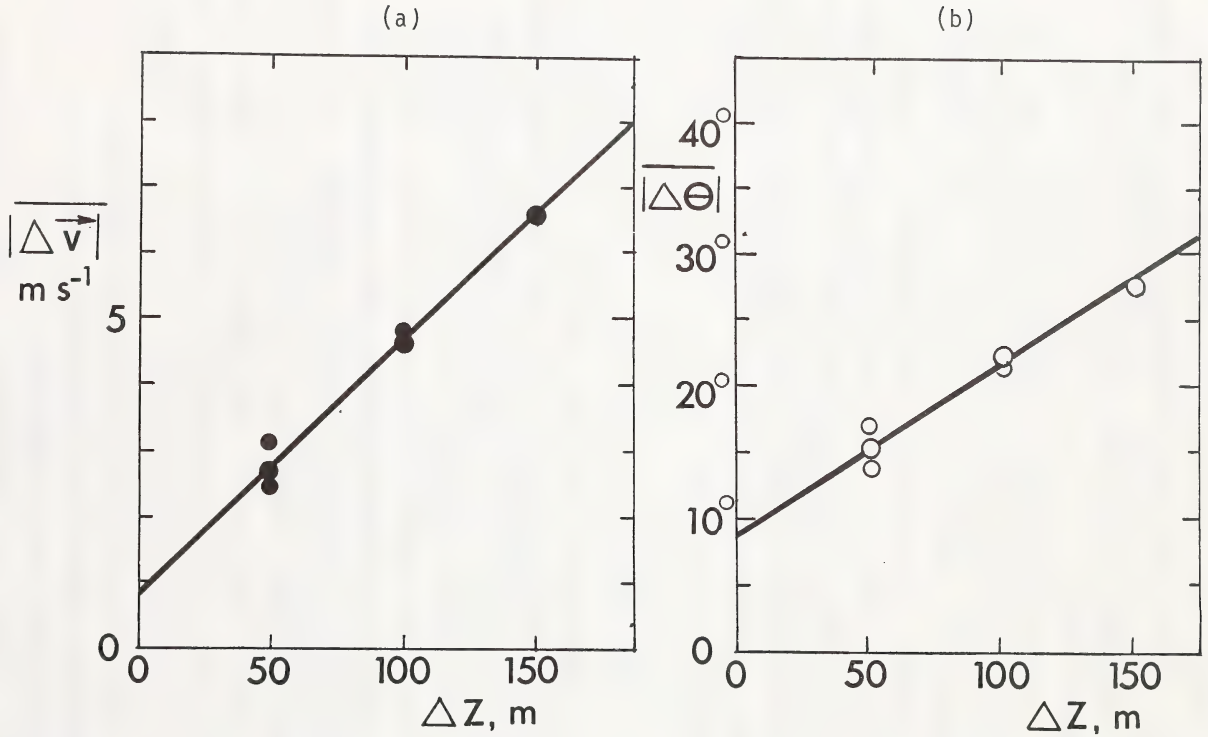


Figure 15. Mean magnitude of vector differences (a) and directional differences (b) between Doppler winds as functions of height difference between levels. The straight lines passing through the points have been used to determine mean vertical gradients of wind shear.

against height difference, as in Figure 15, a linear trend emerged. The substantial vertical intercept of 9° on this plot is unlikely to be due entirely to non-linearity of the vertical gradient of wind direction, and is more probably indicative of variance or error in individual wind estimates. The slope of the fitted line, 13°/100 m, characterises the typical angular difference between winds at two levels, irrespective of algebraic sign.

Examination of the diurnal variation of wind shears, particularly with respect to the occurrences of larger than average wind differences, revealed no marked effects within the available statistics.

4.5 CHINOOKS

Chinook events occurring during the study have been identified and are listed in Appendix 8.4. Eight individual cases have been selected for further detailed study. These cases fall into two time periods: 1980 December to 1981 February, and 1982 November to 1982 December. Detailed presentations of these case studies are given in section 4.5.1 below. In all cases, monostatic and Doppler sodar records at SPBK were compared with surface wind and temperature data. For the cases of 1982 November and December, additional monostatic sodar data from MRC and CIA were included in the analysis. The main features coming out of these detailed analyses are presented in the following.

The descent of the warm Chinook air mass could be followed on monostatic sodar records, and correlated well with the descent of westerly flow observable in Doppler sodar wind profiles. A general feature of the data was a tendency for surface temperatures to rise several hours before the actual surfacing of the westerly winds. During the period of rising surface temperatures, strong westerlies were clearly present in the Doppler data within 250 m of ground level. In some cases, the warming effect of the Chinook was detected at the surface even though the westerlies failed to reach the surface. This effect indicated that radiative heat transfer may play an important role in Chinooks.

Multiple-site monostatic sodar observations clearly showed the eastward progression of the Chinook boundary between warm and cold air masses aloft. The slope of the frontal surface for the event of 1982 November 25 to 26 was determined to be 1:1.70. Accurate prediction of the surfacing of the westerlies at a given site using sodar data as a guide would not appear to be reliable, as the descent of the warm air mass is not linear with time. The situation may be further complicated by Arctic frontal movements associated with the Chinook.

The time behaviour of the wind profiles in these Chinooks was often quite complex. Quasi-periodic variations in wind speed and direction were observable in the case studies of 1982 November and December. These variations may have been due to lee waves or perhaps to lee-side cyclogenesis in which the westerly Chinook flow over the Rocky Mountains set up small-scale circulations which did not register on the reporting grid used for synoptic weather maps. Because of the inherent inability of instruments at a single site to distinguish between temporal and spatial variations, these last interpretations of the data are conjectures which may be tested only by means of multi-site wind profiling experiments.

4.5.1 Chinook Case Studies

4.5.1.1 1980 December 6 to 11. During the period 1980 December 6-11, Calgary and the surrounding area were under the influence of a characteristic strong Chinook condition. The data for this entire period are shown in Figure 16. A careful examination of these data clearly shows that there were three distinct periods of strong westerly winds with corresponding increases in surface temperature.

The first period may be taken from 1200 MST on December 7 to 1400 MST on December 8. Although surface temperature started to rise at 2300 MST on December 6 and had increased by 17°C by 1200 MST on December 7, the winds started to increase only after that time and remained strong and westerly until 1400 MST on December 8. At

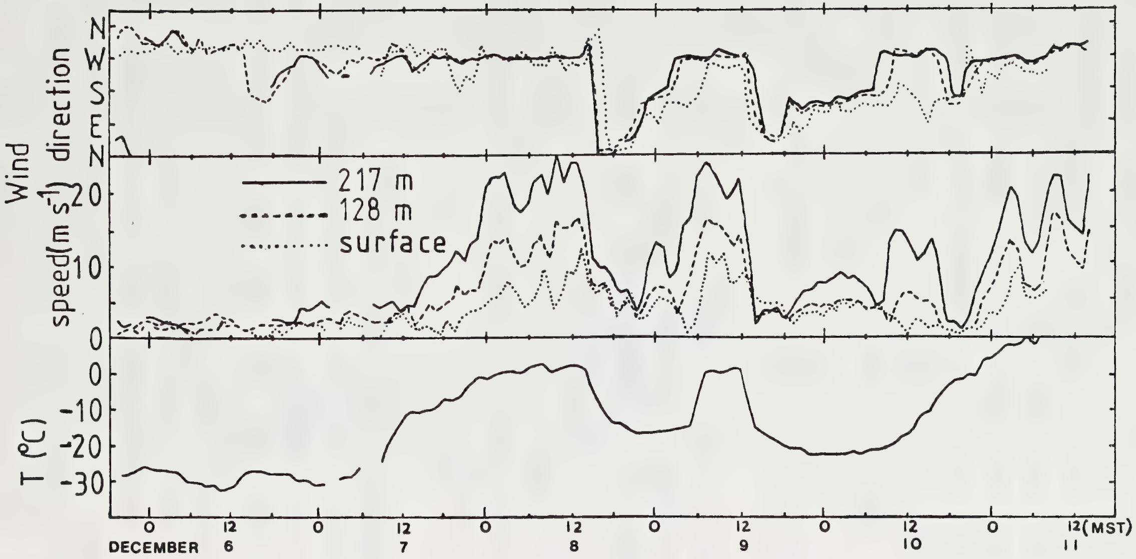


Figure 16. Time series (hourly means) of surface temperature, and wind speed and direction at various heights at SPBK, measured by the Doppler sodar for 1980 December 6 to 11.

this time, the wind speed decreased suddenly and became northerly and the surface temperature dropped by about 20°C. This event was associated with the passage of the Arctic front as suggested by surface analysis maps. Again, at 0500 MST on December 9, surface temperature increased by 14°C marking the beginning of another Chinook period. This warm spell lasted for about six hours during which winds were strong and westerly. The interesting feature of a Chinook that may not reach the ground is clearly revealed in the data for 1000 to 1500 MST on December 10. During this period, the surface winds were light and from S/SE while the upper level flow was strong and westerly. The gradual rise in surface temperature could have been caused by the heat radiated from the upper level warm air.

The three distinct warming periods could also be visualised from the monostatic sounder records in which an elevated layer was seen to move up and down, reaching the ground at different times which agreed well with the ground level warming times. Thus, the three warming periods may be regarded as a result of the same Chinook which was being pushed back and forth by the passage of the Arctic front in this region.

4.5.1.2 1980 December 24 to 30. Another period of chinook flow identified during the course of observations is 1980 December 24 to 30. The wind and temperature data for this period are given in Figure 17. In this case also, there were instances when upper level flow was strong and westerly while the ground observations showed light to moderate northerly winds. The Chinook flow reached ground around 2000 MST on December 26. At this time, winds were strong and westerly at all levels and ground temperature also increased further to 12°C, a value much above the normal for this time of the year. This warm period continued until December 30; however, the magnitude of wind kept on varying from moderate to strong for most of this period.

4.5.1.3 1981 January 17 to 22. Another period of warm

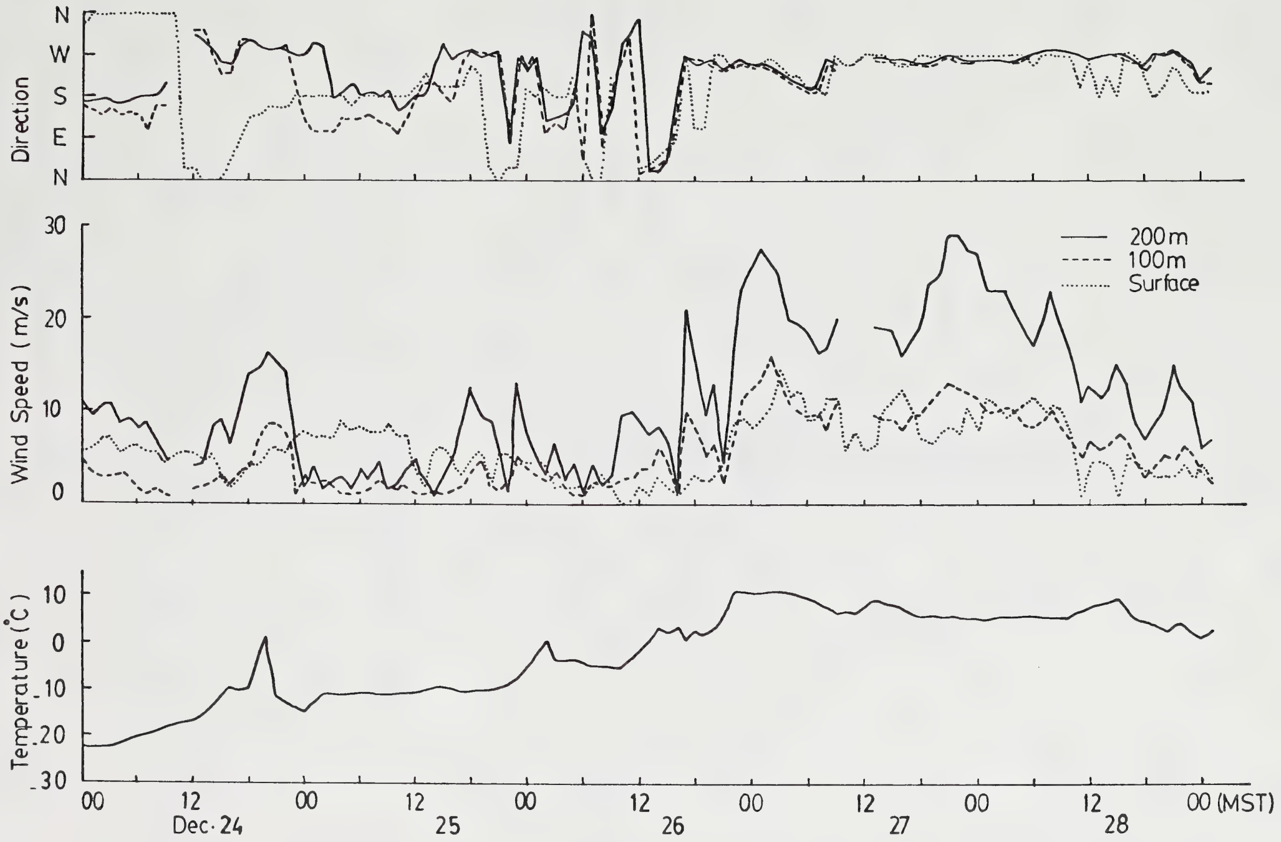


Figure 17. Time series (hourly means) of surface temperature, and wind speed and direction at various heights at SPBK, measured by Doppler sodar for 1980 December 24 to 28.

weather experienced at Calgary was January 17 to 22, when the surface temperature rose to well above normal for this time of the season. The wind and temperature data have been plotted and are shown in Figure 18. From these data, one can clearly visualise that there had been several distinct periods when Chinook flow reached the ground. The surface temperature shows distinct variations which, in the absence of wind data, might have been interpreted as due solely to diurnal variations. However, the wind data show that the peaks in surface temperature correlate well with the ground level westerly wind maxima. The upper level winds started to increase at 0200 MST on January 21 and by 0600 MST they were fairly strong and westerly. However, the ground level temperature started to rise after 0800 MST and winds became strong and westerly at 1300 MST. The ground level wind peak shows a time lag of five hours with reference to the upper level wind speed maximum. This lag is the time taken by the Chinook flow to reach the ground.

The monostatic sounder record obtained during this period at SPBK also showed several instances of Chinook flow reaching the ground. On January 21, it showed a Chinook layer which disappeared shortly after 1100 MST, after which no structure was observed on the facsimile chart. The structure reappeared after 1600 MST. This observation is very typical of the Chinook flow reaching the ground.

4.5.1.4 1981 February 12 and 13. The wind and temperature data for the Chinook period of February 12 and 13 are shown in Figure 19. Like other Chinook events, this Chinook was also accompanied by a strong westerly wind at higher levels which became westerly and strong at the ground level at a later time. Temperature also increased considerably. Figure 19 shows strong westerly upper level winds after 1500 MST on February 12, which then decreased around midnight. Winds again picked up around 1600 MST on February 13 and became strong and westerly by 1900 MST, thereafter decreasing again. The surface temperature started to increase gradually at 0300 MST on February 13 and increased steadily until it reached 20°C at 1800 MST. However, ground level winds became strong

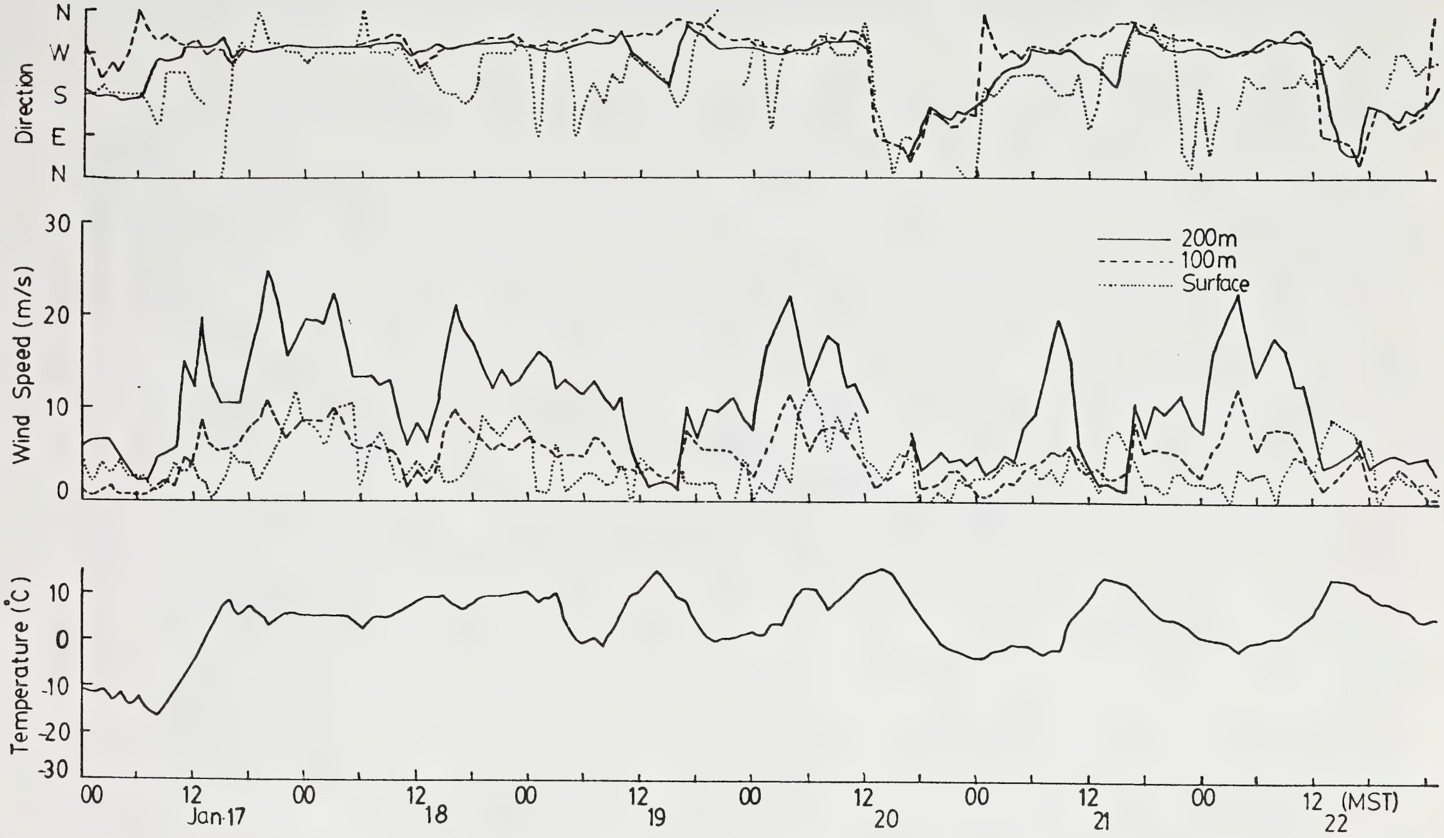


Figure 18. Time series (hourly means) of surface temperature, and wind speed and direction at various heights at SPBK, measured by Doppler sodar, for 1981 January 17 to 22.

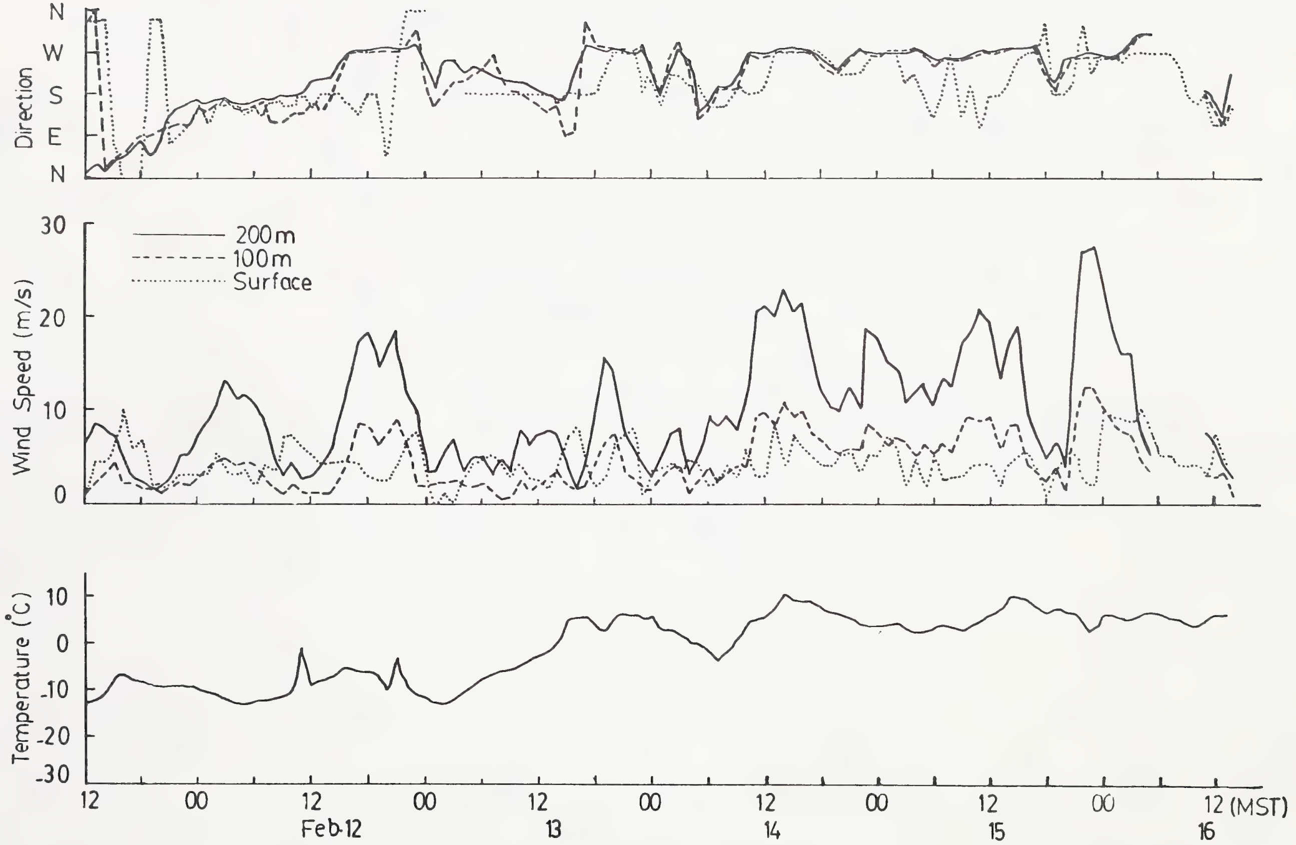
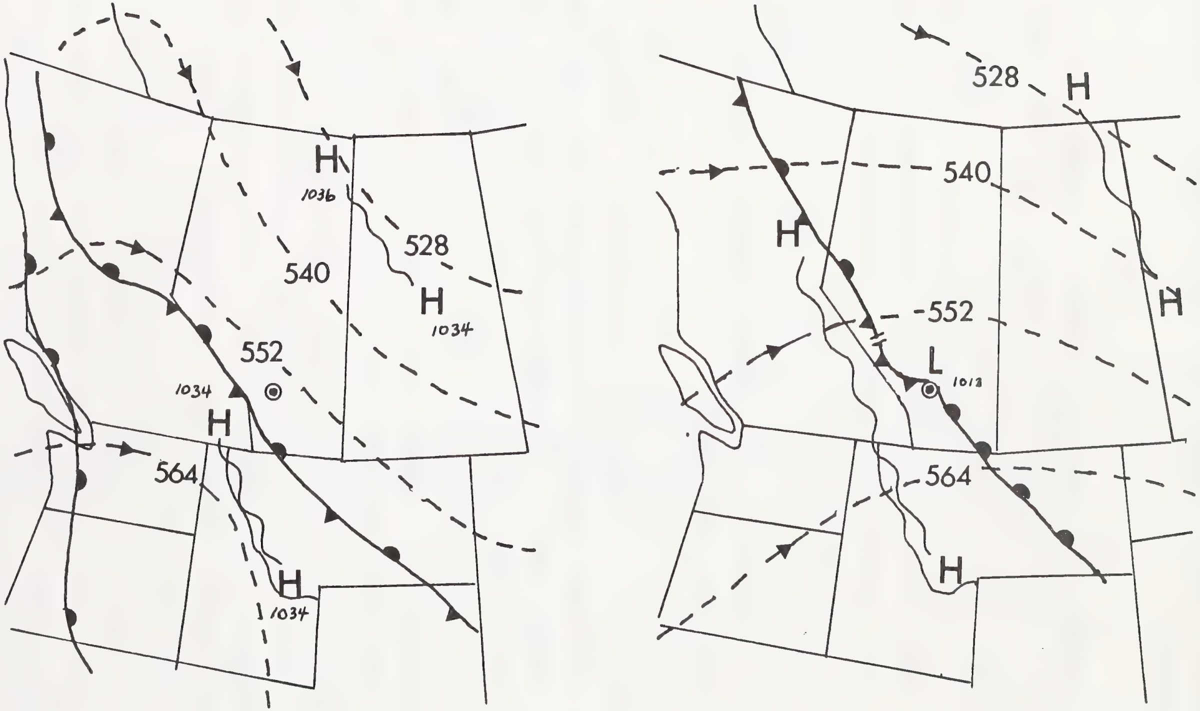


Figure 19. Time series (hourly means) of surface temperature, and wind speed and direction at various heights at SPBK, measured by Doppler sodar, for 1980 February 12 to 16.

and westerly at 2000 MST. The above observation of the Chinook was further supported by surface analysis maps and facsimile records of the monostatic sounder.

4.5.1.5 1982 November 25 and 26. Synoptic conditions of the November 25 and 26, before and after the passage of the Arctic front through Calgary, are given in Figure 20. As is typical with most retreating Arctic fronts, the upper level ridge line shifted eastward across the Continental Divide (the southwestern border of Alberta). The upper level winds became southwesterly by late on 82-11-26, while at the surface a weak low pressure area developed northeast of Calgary. The surface ridge line extending from eastern British Columbia into Montana on the synoptic maps of both days is characteristic of Chinook conditions.

Figure 21 gives height-time analysis of hourly vector averages of wind speed and direction obtained with the Doppler sodar. Surface wind speeds and directions have been used to extend the isotachs to ground level. Also shown on this diagram are the base and top of the prominent acoustic echo layer, and near-surface temperature levels. These show that the frontal transition zone passed SPBK between 0500 and 1900 MST on 82-11-26. The initial rise in temperature corresponds well with the grounding of base (B) of the descending echo layer observed on the monostatic sodar record. The descent of the top (T) of the echo layer was more irregular, finally reaching ground level about 1700 MST. This occurrence is at variance with the position of the Arctic front shown in Figure 20, which shows that by 1700 MST the front was well to the east of Calgary. This discrepancy may be partly due to the uncertainty in locating the surface front, given the relatively few data available on the surface map. There is also some uncertainty in determining when the echo layer reached ground. Quite often, as an elevated layer approaches ground, a ground-based inversion layer also develops, especially when winds are light. Therefore, extrapolation of the descending layer is necessary. This may have masked the real position of the air mass discontinuity between 1100 and 1900 MST on



25 NOV 82 1700 MST

26 NOV 82 1700 MST

Figure 20. Synoptic conditions for the Chinook of 1982 November 25 and 26. Dashed lines are contours of a constant pressure-surface. Numbers on the contours give the height of the constant-pressure surface in decametres ASL. Arrows on contours show the direction of the geostrophic wind. Small numbers beside high and low cells (H and L) give sea level pressure in mb.

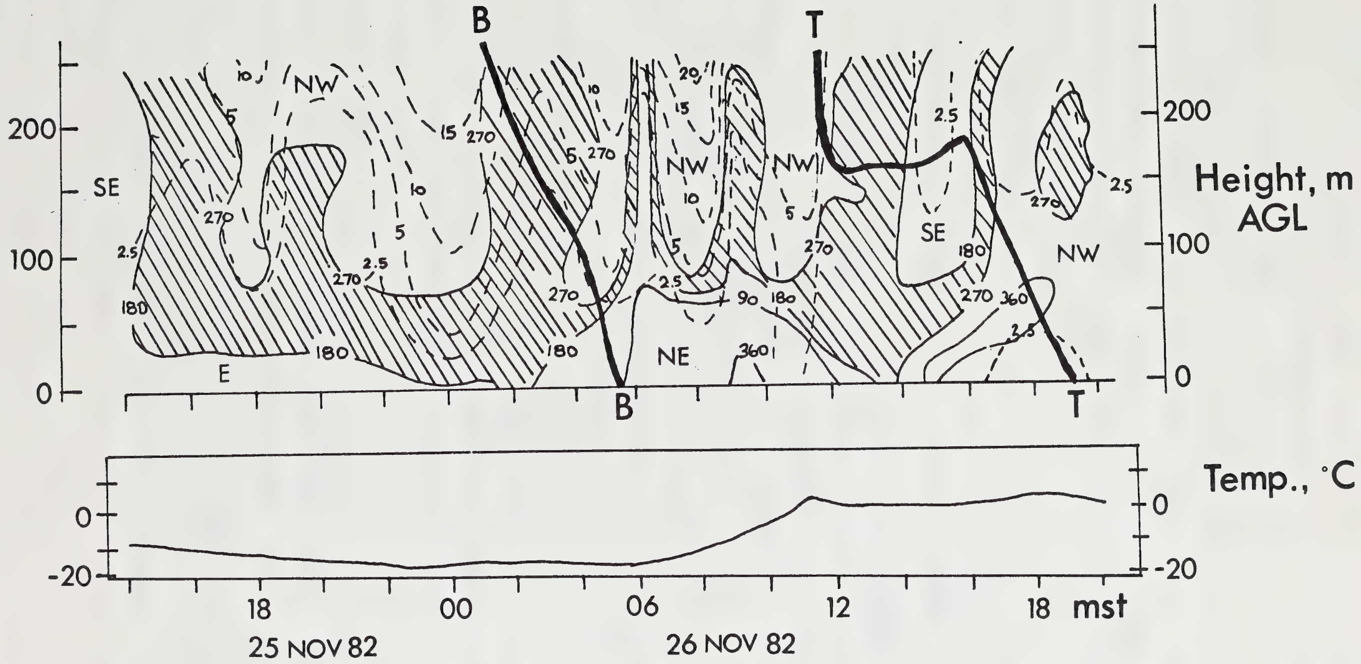


Figure 21. Height-time analysis of hourly Springbank winds for the Chinook of 1982 November 25 and 26. Solid lines are isogons (contours of equal wind direction); dashed lines are isotachs (contours of equal wind speed in m/s). Heavy lines mark the descent of the bottom (B) and top (T) of the layer observed on the monostatic sodar. Regions of southwesterly winds (between the 180° and 270° isogons) are shaded. The lower graph gives the surface temperature at Springbank.

82-11-26. The top of the echo layer showed considerable time variation, perhaps due to a combination of factors.

The distribution of the winds above 50 m AGL obtained by the Doppler sodar deviates from Lester's conceptual model of the Chinook in two ways. Strong westerly winds occurred before and during the passage of the frontal zone. The winds were light after the frontal zone passed through the region. Except for the earliest times shown on the left of the time sections, the winds were generally from the west at 50 m AGL. The strongest winds appeared to be quasi-periodic over three to five hours with a strong correlation with WNW directions. The isotachs on the left of each of the three maxima were vertical. This pattern suggests that three vertically sheared descending layers existed within the general descending layer observed by the sodar.

Near the surface, winds remained light throughout the entire period. Calgary experienced a strong build-up of pollution on this day. The occurrences of northerly and northeasterly winds within the transition zone are perhaps associated with the weak cyclone shown near Calgary in Figure 20.

Figure 22 shows the descent of the echo layer observed by monostatic sodars at SPBK, MRC, and CIA. The descent is well correlated at the three stations. As the cold air moved eastward, the base of the echo layers passed SPBK, MRC, and CIA in succession at a horizontal speed of about 6 km/h (1.7 m/s). The base of the transitional layer above the three stations could be determined, and after correcting for the altitude difference of the stations, the slope of the transition surface was determined. In this event, the average value of the slope was about 1:1.70.

4.5.1.6 1982 December 7 to 9. Synoptic conditions for this period are shown in Figure 23. These fulfilled very nearly the classical model of a Chinook. A cold Arctic anticyclone moved southeastward across Alberta on 82-12-07. The coldest air reached Calgary when the high centre was located in western Saskatchewan (central high 1051 mb). A strong northwesterly flow prevailed at

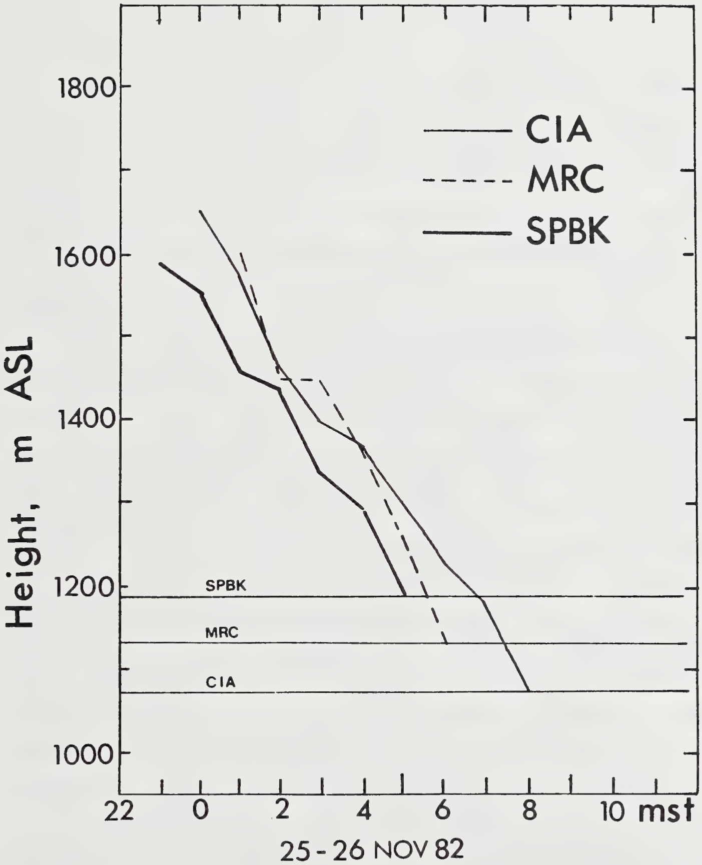
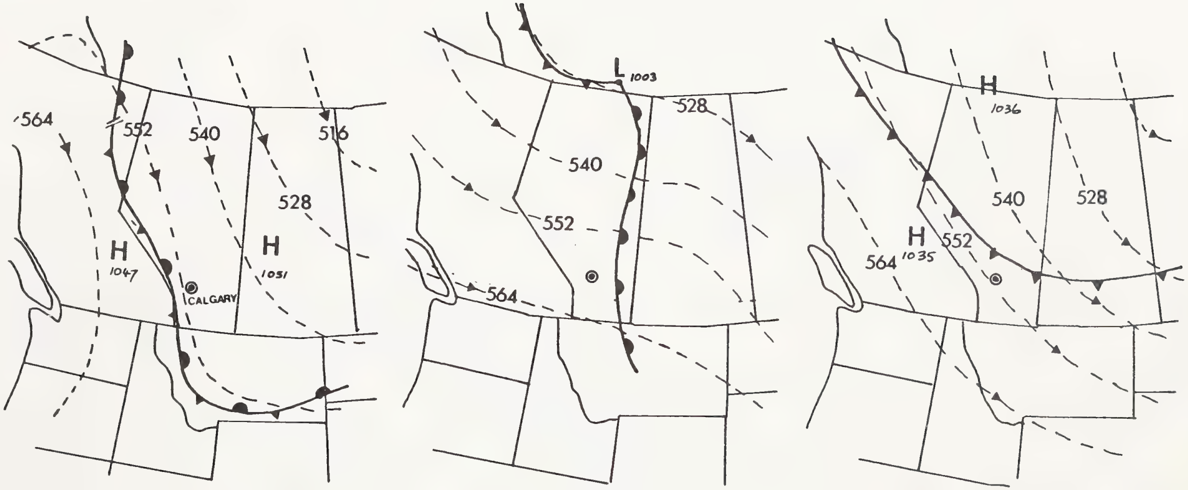


Figure 22. Descent of base of echo layer observed on monostatic sodar records during the Chinook of 1982 November 25 and 26.



7 DEC 82 1700 mst

8 DEC 82 1700 mst

9 DEC 82 1700 mst

Figure 23. Synoptic maps for the Chinook of 1982 December 7 to 9. Dashed lines are height contours of a constant pressure surface, with heights shown in decametres above sea level. Arrows on the contours show the direction of the geostrophic wind.

the 500 mb level. A strong upper level disturbance and the associated surface system progressed across British Columbia on 82-12-08, as the cold air moved farther eastward. This resulted in westerlies at 500 mb and the development of a cyclone on the Arctic front near the northern border of Alberta. As the surface low proceeded southeastward, ridging re-established itself over British Columbia at 500 m and strong northerly flow carried the Arctic air southward towards Calgary.

Mesoscale wind and inversion structures for this classical case are reflected in Figure 24 at Springbank. Surface temperatures began increasing at about 1900 MST, and reached a maximum at about 1700 MST the next day. The temperature increase corresponded well with the grounding of the base and top of the echo layer observed on the monostatic sounder records at SPBK, MRC, and CIA.

Wind speeds, with a few minor exceptions (e.g., 82-12-08, 0600 MST) remained very light at the surface until 1700 MST, when the top of the transition zone reached the surface. Figure 24 shows that winds were relatively strong and southwesterly until 82-12-09, 0000 MST, when speeds dropped off and a new echo layer developed. The latter feature appeared to be associated with increasing stability caused by surface cooling and light winds, rather than being due to an air mass exchange. After the westerlies decreased, the winds became more northerly with the return of the cold air later in the period. Masking of the warm boundary of the transition zone appeared to be a problem, as in the Chinook of November 25 and 26, because of local radiational effects. For example, a comparison of Figure 20 with Figure 23 shows a discrepancy in frontal position (warm boundary of transition zone) relative to SPBK (about 25 km west of CIA). The surface front appears too far east in both cases.

A periodic variation again occurred with the westerly winds in the upper part of the 250 m layer. A seven-hour interval between maxima was about average. The base of the sodar echo layer in Figure 24 shows a slope parallel to the 270° isogon between 1900 and 2200 MST on 82-12-07. This feature suggests stratification of the wind distribution within the descending layer.

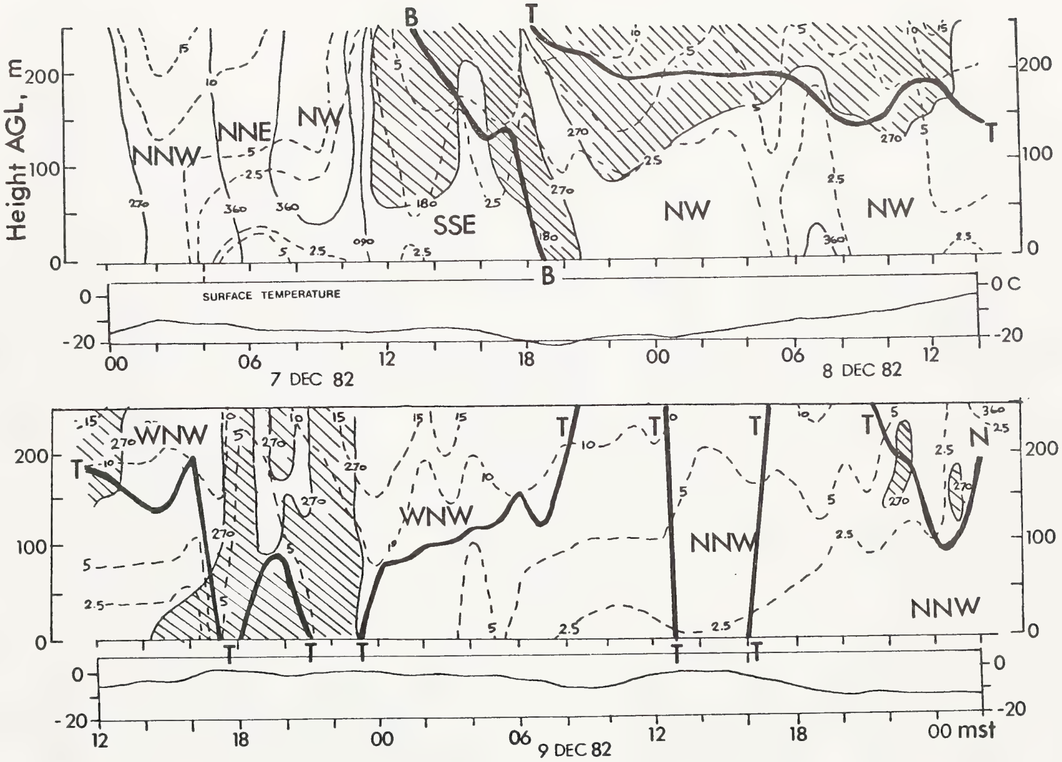
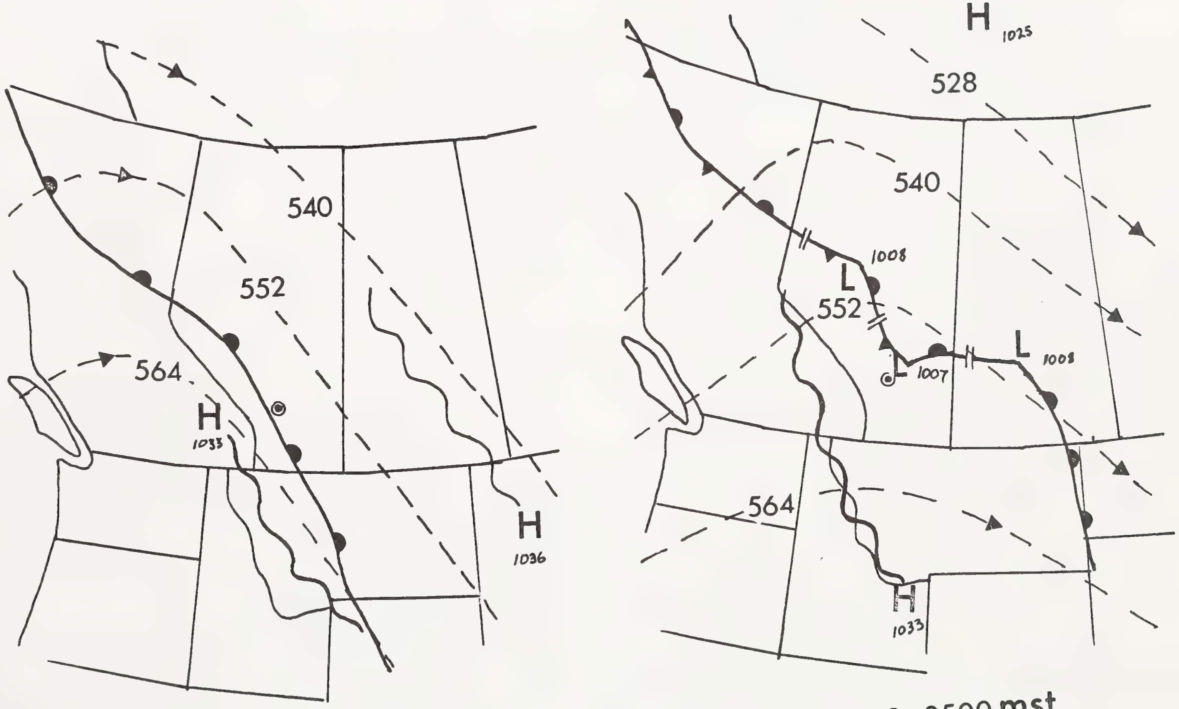


Figure 24. Height-time analysis of hourly Springbank winds for the Chinook of 1982 December 7 to 9. Solid lines are isogons (contours of equal wind direction); dashed lines are isotachs (contours of equal wind speed in m/s). Heavy lines mark the descent of the bottom (B) and top (T) of the layer observed on the monostatic sodar. Regions of southwesterly winds are shaded. The lower graph gives the surface temperature.

The change of wind direction and the fall of temperature prior to 1900 MST on 82-12-07 in Figure 24 corresponds well to the movement of the cold anticyclone across Alberta on the that date (Figure 23). A comparison of monostatic sounder records at SPBK, MRC, and CIA showed a coherent inversion structure across Calgary as was found in the previous Chinook described (see Figure 22). However, the base (cold edge of the transition zone) was moving much more rapidly in this case than in the last. Speed was estimated at 30 km/h (8.3 m/s). Therefore, plots of hourly average echo layer heights were not very informative, since the base of the layer moved from SPBK to CIA in about 50 minutes. There was a good agreement in layer features from site to site. For example, the increase in southeasterly flow and the decrease in temperature just prior to the passage of the base of the transition layer at SPBK was well-correlated with the appearance of another lower layer echo (not shown) at SPBK, MRC, and CIA.

4.5.1.7 1982 December 11 and 12. Synoptic conditions are illustrated in Figure 25. After the return of the Arctic front early on 82-12-10, a shallow layer of cold air remained over the study area for the next 36 hours. These conditions were supported at 500 mb with ridging over British Columbia and northwesterly winds over the Calgary area. By 82-12-11, a series of rapidly moving upper air disturbances had flattened the upper ridge and pushed it eastward, producing southwesterly flow across the divide (Figure 25) at the surface. The Arctic front moved eastward, with the most rapid movement being over southern Alberta and Montana. The unique characteristic of this Chinook case was the establishment of a series of weak cyclonic circulations on the Arctic front, north and east of Calgary. Only the southernmost low showed extensive eastward movement. The low near Calgary intensified and then weakened in phase with rapidly moving upper level disturbances. The height-time section of winds and layer echo boundaries for SPBK for December 11 and 12 is shown in Figure 26. The surface temperature record at the bottom of Figure 26 shows that the major warming at



11 DEC 82 0500 mst

12 DEC 82 0500 mst

Figure 25. Synoptic maps for the Chinook of 1982 December 11 and 12. Dashed lines are height contours of a constant pressure surface, with heights shown in decametres above sea level. Arrows on the contours show the direction of the geostrophic wind. Small numbers beside high and low pressure cells give the sea level pressure in mb.

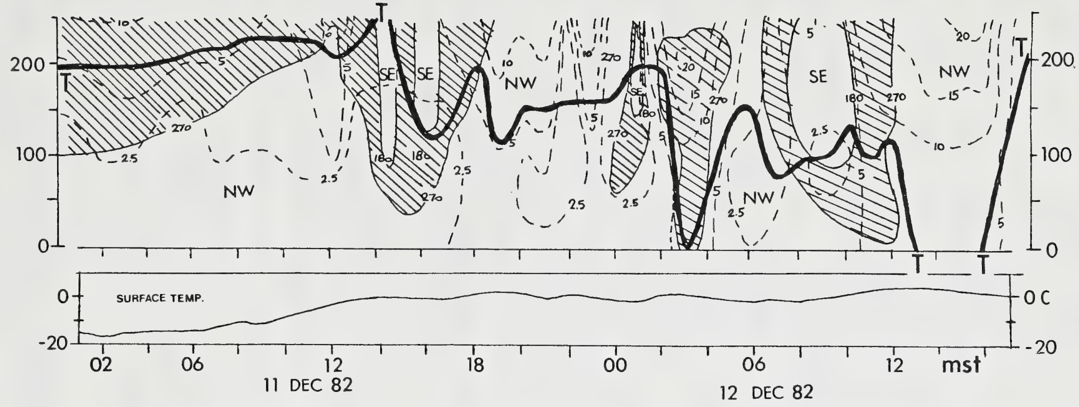


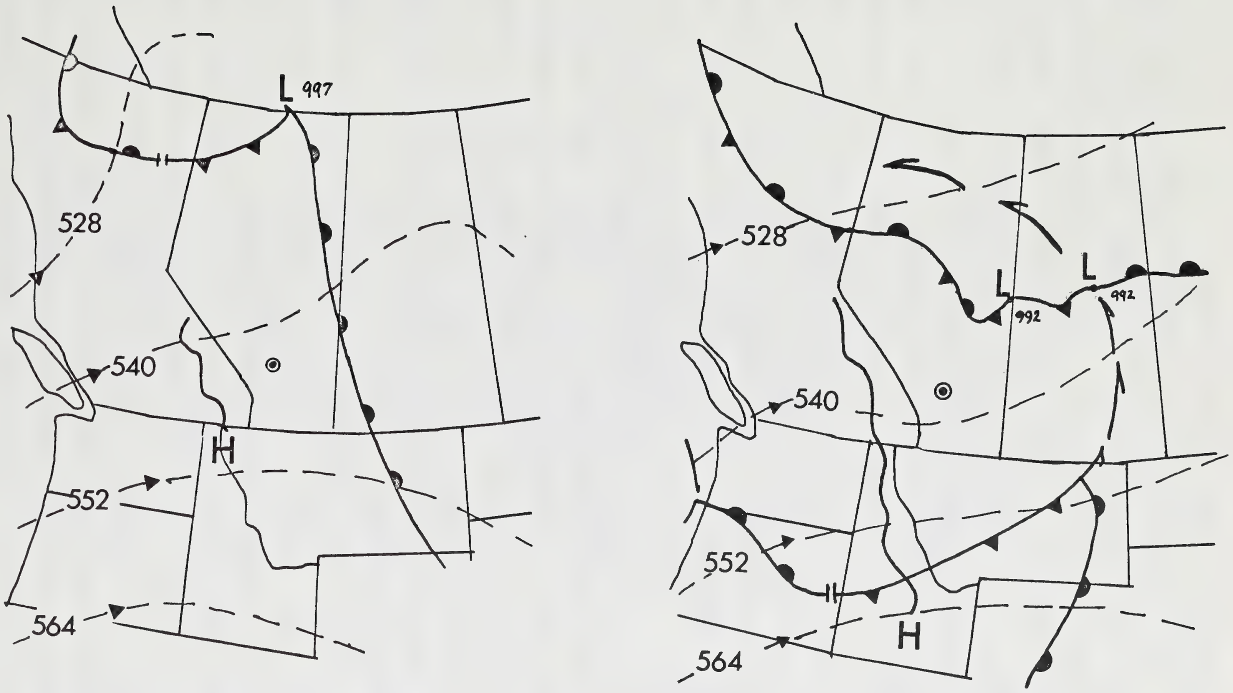
Figure 26. Height-time analysis of hourly Springbank winds for the Chinook of 1982 December 11 and 12. Solid lines are isogons (contours of equal wind direction); dashed lines are isotachs (contours of equal wind speed in m/s). Heavy lines mark the position of the top (T) of the layer observed on the monostatic sodar. Regions of southwesterly winds are shaded. The lower graph gives the surface temperature.

SPBK occurred on December 11. No well-defined elevated echo layer was perceptible on the SPBK sodar records, so only the top of the surface based echo is shown. The sodar records for MRC and CIA, to the east, did show elevated layers as well as a surface-based echo layer. This structure suggests a very stable cold air mass over MRC and CIA with a shallow transition zone over the higher terrain to the west. At SPBK (Figure 26), the top of the stable layer descended from 1400 MST on 82-12-11 until 1300 MST on 82-12-12. The descent was irregular, with a large vertical excursion at 0300 MST on 82-12-12 as strong westerly winds penetrated to the surface. Thereafter wind speeds decreased and the surface echo returned until 1300 MST when strong westerly winds penetrated to the surface for about three hours. Winds at all levels subsequently decreased, indicating a return of the cold air after 1600 MST.

While the latter wind event was seen on the sodar records at all three locations, the earlier, briefer event (0300 MST) was not seen at CIA, corresponding to an increase in the depth of the cold air at that location between 2300 MST on 82-12-11 and 0400 MST on 82-12-12. An unusual feature shown in Figure 26 is the appearance of three weak southeasterly wind features at intervals of 9 to 10 hours (82-12-11, 1400-1600 MST, and 82-12-12, 0100 MST and 0800-1100 MST). It is suggested that these features may represent the influence of the minor low pressure area that appears northeast of CIA in Figure 25. A similar weak southeasterly wind event occurred about 1500 MST on 82-11-26 as shown in Figure 20, when another weak surface cyclone was near CIA.

4.5.1.8 1982 December 15 and 16.

Synoptic conditions for this case are given in Figure 27. This period was characterised by at least two upper air disturbances. With the first disturbance, the Arctic front retreated from the Calgary area by almost midday of 82-12-15. By the afternoon, the front was well to the east and the first of a series of cyclones developed in northern Alberta. Winds at the 500 mb level remained westerly until the next afternoon when a strong upper level disturbance carried a Pacific frontal system



15 DEC 82 1700 mst

16 DEC 82 1700 mst

Figure 27. Synoptic maps for the Chinook of 1982 December 15 and 16. Dashed lines are height contours of a constant pressure surface in decametres ASL. Arrows on the contours indicate the direction of the geostrophic wind. Small numbers beside low pressure cells give the sea level pressure in mb.

well into Saskatchewan through central Alberta.

Figure 28 shows the top of a descending echo layer which corresponds in time with the frontal passage. Otherwise, SPBK appears to be under the influence of local radiational effects on the warm side of the frontal zone. The variation in the height of the ground-based echo layer supports this interpretation, with the lowest heights being at midday and the highest at night. The SPBK temperature record shows that the diurnal temperature variation was clearly superimposed on an upward temperature trend for these days. The trend was apparently due to the continued injection of warm Pacific air from southwest upper winds. Figure 28 shows the top of a descending echo layer which corresponded in time with the first frontal passage. Otherwise, SPBK appears to have been under the influence of local radiational effects on the warm side of the frontal zone. The variation of the height of the ground-based echo layer supports this interpretation with the lowest heights being at midday and the highest heights at night. The SPBK temperature record shows that the diurnal temperature variation is clearly superimposed on an upward temperature trend for December 15 and 16; the trend was apparently due to the continual injection of warmer Pacific air from the southwest.

Upper winds were everywhere westerly in the 250 m deep layer except near the surface. The westerlies gradually increased in speed with the maxima being well-correlated with downward excursions on the top of the sodar echo layer at 0200, 0800, and 1200 MST, on 82-12-16. All of these strong wind events were associated with warm temperatures, the greatest temperature jump (8.5°C in one hour) occurring between 0700 and 0800 MST on 82-12-16. Six to eight wind events (depending on the level examined) occurred between 0200 MST on 82-12-15 and 2100 MST, 82-12-16 (i.e., at two to six hour intervals). The brief variation of wind direction to west-northwest on 82-12-15 at 1000 MST and on 82-12-16 at 1900 MST appears to have been the result of the passing synoptic disturbances discussed in the last section. This case produced the strongest and most persistent Chinook winds for November and December 1982.

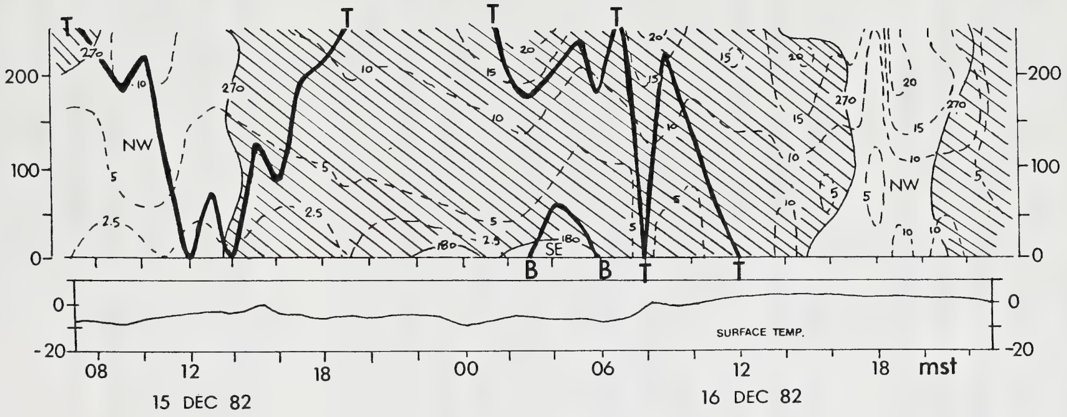


Figure 28. Height-time analysis of hourly Springbank winds for the Chinook of 1982 December 15 and 16. Solid lines are isogons (contours of equal wind direction); dashed lines are isotachs (contours of equal wind speed in m/s). Heavy lines mark the positions of the bottom (B) and top (T) of the layer observed on the monostatic sodar. Regions of southwesterly winds are shaded. The lower graph gives the surface temperature.

5. SUMMARY AND CONCLUSIONS

1. A Doppler sodar at Springbank Airport near Calgary was operated between 1980 November and April 1983 and provided wind information at heights of 100 m, 150 m, 200 m, and 250 m AGL. Contemporaneous data from three stations measuring winds near ground level using conventional instruments were collected for the same period. The Doppler sodar data were found to be self-consistent as well as consistent with near surface measurements.

2. All stations exhibited a seasonal variation in which mean winds tended to be slightly stronger for the six months of the year from January to June. Some differences among the stations could be discerned, possibly due to local topography. Doppler winds showed a systematic increase with height. The prevailing wind direction of Doppler winds was W/WNW.

3. Distributions of wind directions at all stations including those determined by Doppler sodar had a bimodal character with westerly and southeasterly peaks present to a greater or lesser degree. The westerly peak was generally dominant, while the southeasterly peak was smaller and showed greater variability from month to month.

4. Vector-averaged mean wind at all heights measured by Doppler sodar was westerly and increased systematically with height from 2.0 m/s at 100 m to 7.0 m/s at 250 m. Scalar-averaged means of wind speed were somewhat larger, increasing from 3.5 m/s at 100 m to 9.9 m/s at 250 m. Examination of mean winds at different heights gave a uniform mean wind shear of about 4 m/s per 100 m, with a mean directional variation with height of approximately 13° per 100 m.

5. A common feature of the diurnal variation of winds measured at all stations was a tendency for winds to be more northwesterly than average in the morning hours. A second feature was a weak counterflow in the early afternoon. This effect was

present at all heights accessed by the Doppler sodar and may be due to anabatic/katabatic circulation.

6. Wind data obtained during Chinook events showed considerable complexity. The descent of the elevated warm air mass could be followed by monostatic sodars, and was generally associated with the descent of westerly winds as observed by the Doppler sodar. In some cases, although the westerly flow observed by the Doppler sodar had failed to reach ground level, surface warming was observed, indicating that radiative heat transfer plays a significant role in Chinook dynamics. Wind patterns during Chinooks were often disrupted by Arctic frontal movements. Occasional quasi-periodic fluctuations in near-surface winds were also observed. It is evident that the vertical wind profiles provided by Doppler sodars are useful in monitoring Chinook events, but that multi-site wind profile data will be necessary for meaningful analysis of this mesoscale phenomenon.

6. RECOMMENDATIONS

It is recommended that:

1. Alberta Environment establish a permanent climatological station in Calgary, which will make regular use of a Doppler sodar to access winds above 50 m.

2. Identical instrumentation and methods of extraction of data should be employed to monitor near-surface wind at different locations in order to reduce uncertainties in inter-comparison of data. This measure would be facilitated considerably if the same agency were to carry out all the measurements.

3. An extensive and co-ordinated study of Chinooks, employing sodars located at different sites (such as Lethbridge and Brooks), in conjunction with conventional instruments, should be undertaken by Alberta Environment.

4. In further studies of Chinooks, regular and frequent measurements of temperature profiles should be undertaken to aid in the interpretation of data obtained by Doppler and monostatic sodars.

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8. APPENDICES

8.1 DATA ARCHIVE FORMAT

Wind data for seven surface and Doppler stations are organised on a 9-track digital magnetic tape at a recording density of 1600 bpi. Seven files on the tape correspond to the following stations:

File Number	Identifier	Station/Data Type
1	CIA	Calgary International Airport hourly temperatures and winds
2	UCC	Univ.Calgary campus hourly temperatures and winds
3	SPB	Springbank Airport hourly temperatures and winds[a]
4	100	Springbank 100 m hourly Doppler sodar winds
5	150	Springbank 150 m hourly Doppler sodar winds
6	200	Springbank 200 m hourly Doppler sodar winds
7	250	Springbank 250 m hourly Doppler sodar winds

[a] Wind direction and the temperatures are from the Doppler sodar site for the whole data period. Wind speed data are from the sodar site except for 82-01-01 to 82-10-31, when data are from Transport Canada anemometer located at the Springbank control tower.

The type of data storage is "variable blocked" (i.e., logical records of variable length [see format information below] are grouped into physical records of length 2048 ASCII characters).

8.1.1 Surface Data Format

One day of data requires four logical records, as outlined below:

Record	Data Type	Format	Record Length (Characters)
1	year, month, day; station identifier	3I2,1X,A3	10
2	24 hourly temperature values in units of 0.1 degrees Celsius (e.g., -10.3°C appears as -103)	24I4	96
3	24 hourly wind speeds in units of 0.1 m/s (except CIA, where the units are km/h)	24I4	96
4	24 hourly wind directions. 0=north, 90=east, 180=south, 270=west.	24I4	96

The first value of each day corresponds to 0000 MST.
Where the data are averages (as in the wind speeds at UCC and SPBK), the value recorded for a given hour refers to the preceeding 60-minute period.
Missing hours are recorded as 9999 in the appropriate data field.
If a complete day is missing, it is excluded from the data record.
Last four records of each file are zero-filled.

8.1.2 Doppler Data Format

There are no temperature data for the Doppler data files. The format for these files is equivalent to that for the surface data, but with the temperature record (record 2 above) omitted. Thus each day consists of three logical records:

Record	Data Type	Format
1	data/identifier	3I2,1X,A3
2	wind speeds	24I4
3	wind directions	24I4

8.2 DOPPLER SIGNAL PROCESSING

The signal from each Doppler sodar receiver consists of a sinusoid at frequency f due to scattered sound waves, plus additive white background noise. Non-zero winds in the scattering volume cause the sinusoidal component to be Doppler shifted from the transmitted frequency f_0 (1600 Hz) by an amount of Δf which does not exceed 100 Hz for winds less than 27 m/s. The Doppler shift in the received signal is determined by a combination of analog and digital processing.

8.2.1 Analog Processing

The received signal is preamplified and bandpass filtered at a centre frequency of 1600 Hz to reject noise. The filtered signal is then multiplied by an 1800 Hz reference sinusoid and low-pass filtered to heterodyne the signal to a new centre frequency of 200 Hz. This preserves the Doppler shift, apart from a change in sign, and allows the required digitisation rate to be fairly low (800 Hz).

8.2.2 Digital Processing

The output from the 12-bit analog-to-digital converter is subjected to a digital algorithm, implemented on an INTEL 8088 16-bit microprocessor to determine the signal intensity and Doppler shift. Since the digital algorithm requires that the mean value of the signal be zero, an initial stage of digital filtering was applied to reject any DC component in the signal.

Two forms of algorithm were used in the course of this study. The first, "real covariance," based upon Owens (1977), was used from the beginning of the study until the end of May 1981. In the summer of 1981, the microprocessor software was converted to the second algorithm, "complex covariance." Neff et al. (1980) have demonstrated superior performance of the complex covariance estimator in the noisy signal environment typical of Doppler sodar applications. The two algorithms are described in detail below.

8.2.2.1 Real covariance. Let a series of N digitised values be designated $[x_1,x_2,x_3,....,x_N]$. Let the mean of these values be zero (i.e., no DC component). Autocorrelation estimates at zero and unit lag are then calculated:

$$R_0 = \sum_{i=1}^{N} x_i^2 \qquad \text{(proportional to signal power)}$$

$$R_1 = \frac{N}{N-1} \sum_{i=1}^{N-1} x_i x_{i+1}$$

Since the autocorrelation function of a pure sinusoid is a cosine function, it follows that an estimate of the average signal frequency is

$$\Delta f = \frac{f_{DIG}}{2\pi} \cos^{-1} \frac{R_1}{R_0} \qquad \text{(real covariance estimate)}$$

where f_{DIG} is the digitization rate.

8.2.2.2 Complex covariance. Let a series of N digitised signal values be designated $[x_1,x_2,.....,x_N]$. The mean of the values is assumed to be zero, and N is an even number. This series of N real values is then visualised as a sequence of N/2 complex numbers:

$$z_k = x_{2k-1} + j\, x_{2k}, \qquad k = 1,2,....,N/2$$
$$j = \sqrt{-1}$$

The complex auto-correlation function is then calculated at zero and unit lag:

$$A_0 = \sum_{k=1}^{N/2} z_k^* \cdot z_k$$

$$A_1 = \sum_{k=1}^{N/2-1} z_{k+1}^* \cdot z_k$$

where the asterisk denotes complex conjugate. The signal power is proportional to A_0, and the Doppler frequency shift is given by

$$\Delta f = \frac{1}{4\pi\tau} \tan^{-1} \left[\frac{\text{Im } A_1}{\text{Re } A_1} \right]$$

where $\frac{1}{\tau}$ is the analog-digital conversion sampling frequency. This Doppler shift is measured from a centre frequency of $1/4\tau$.

8.3 SURFACE WIND DISTRIBUTIONS

The following figures show monthly distributions of surface wind directions for the period November 1980 to March 1983:

Directions:
N = north (true)
E = east
S = south
W = west
C = calm

Stations:
CIA = Calgary International Aiport
UCC = University of Calgary Campus
SPBK= Springbank Airport

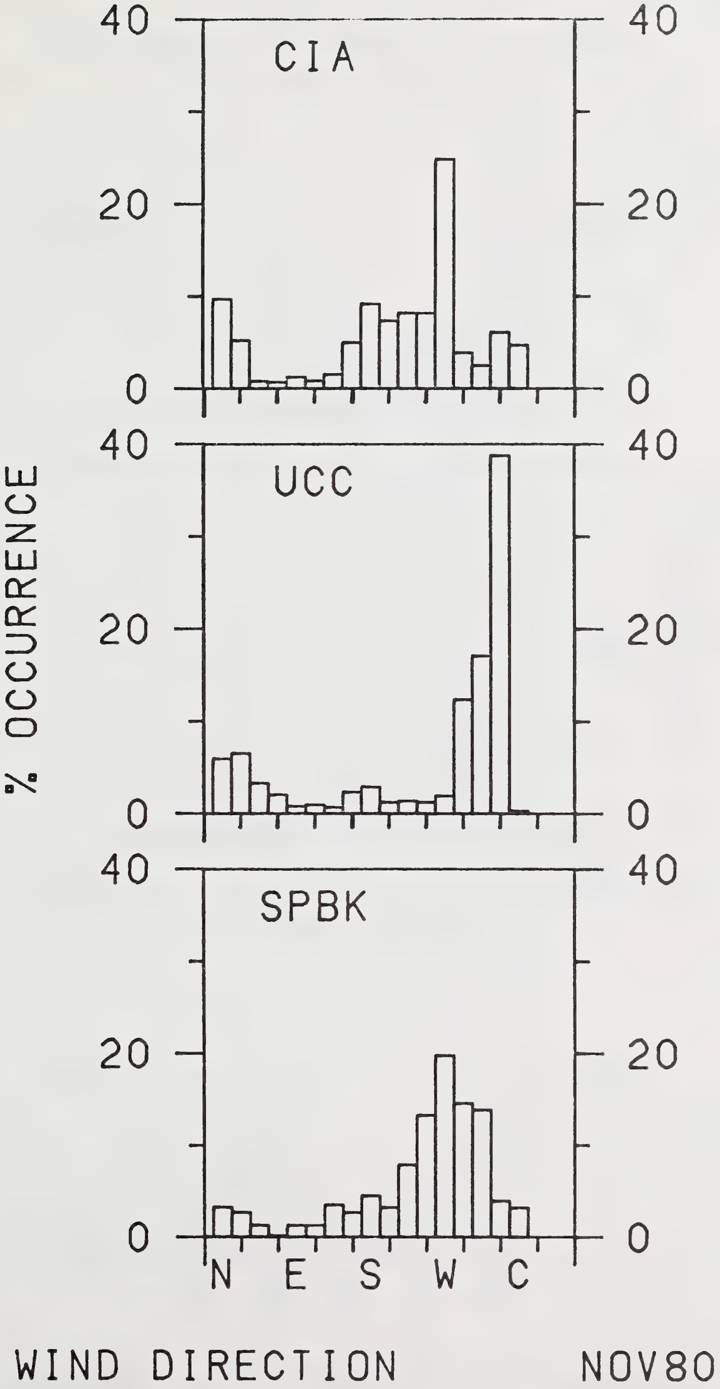

Figure 29. Distributions of surface wind directions for the month of November 1980.

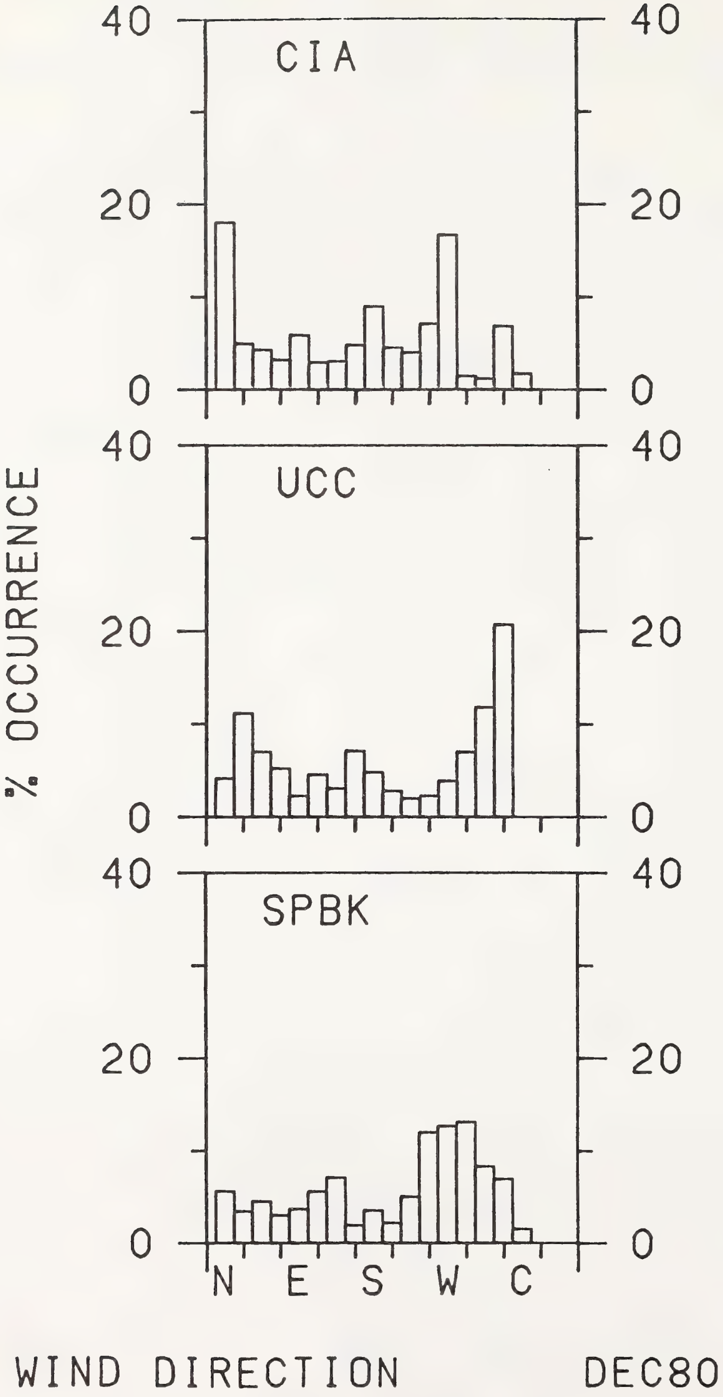

Figure 30. Distributions of surface wind directions for the month of December 1980.

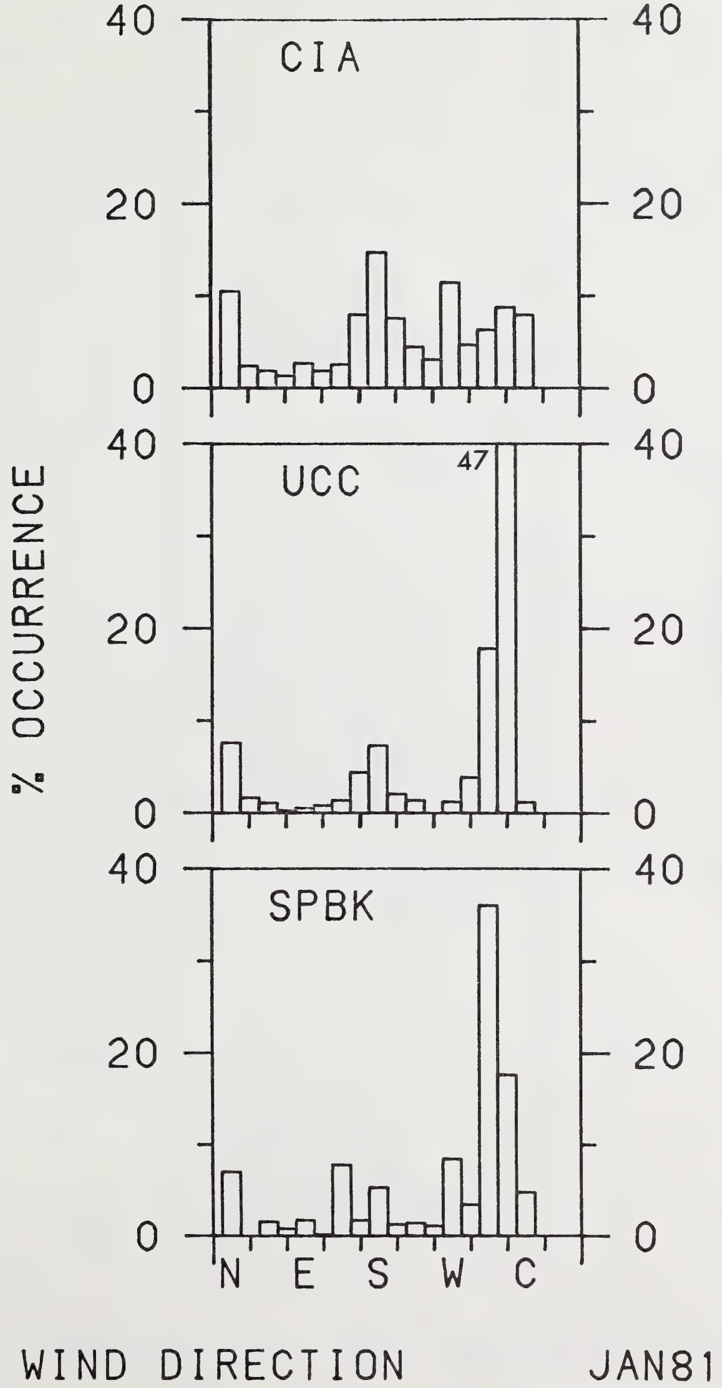

Figure 31. Distributions of surface wind directions for the month of January 1981.

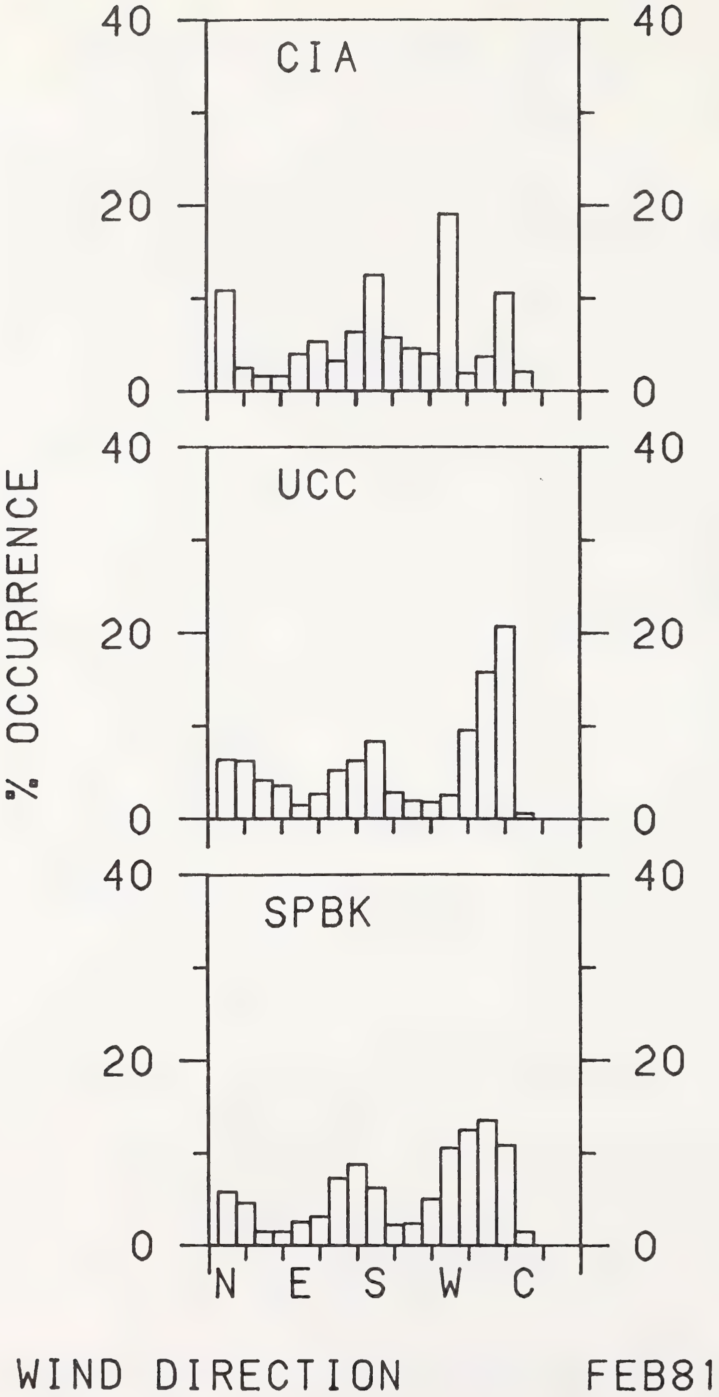

Figure 32. Distributions of surface wind directions for the month of February 1981.

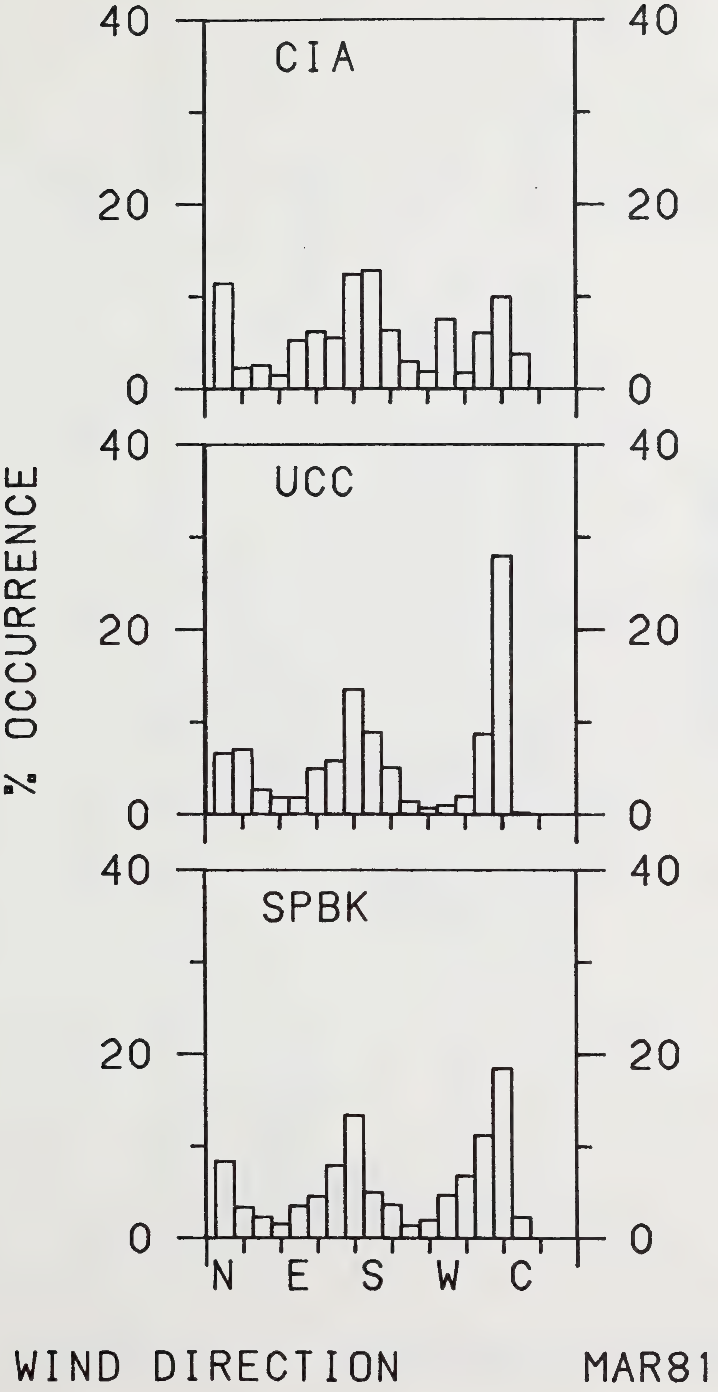

Figure 33. Distributions of surface wind directions for the month of March 1981.

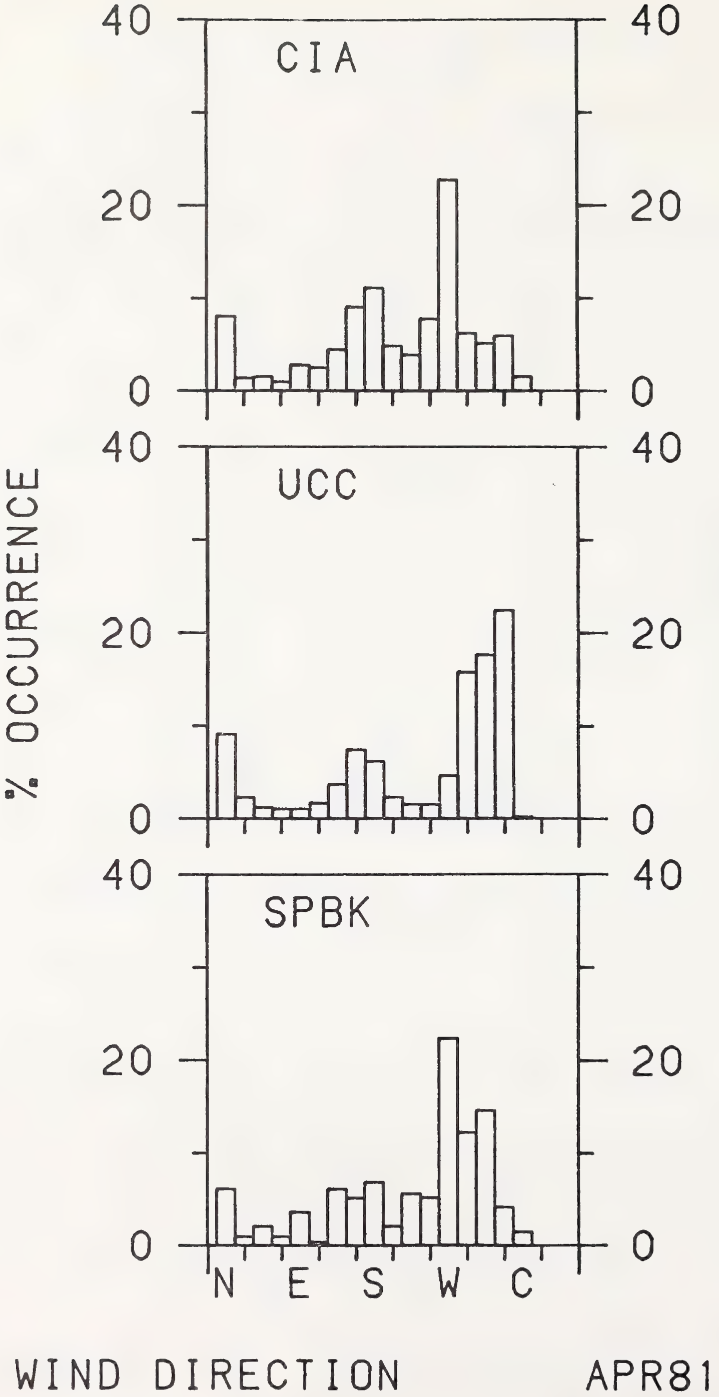

Figure 34. Distributions of surface wind directions for the month of April 1981.

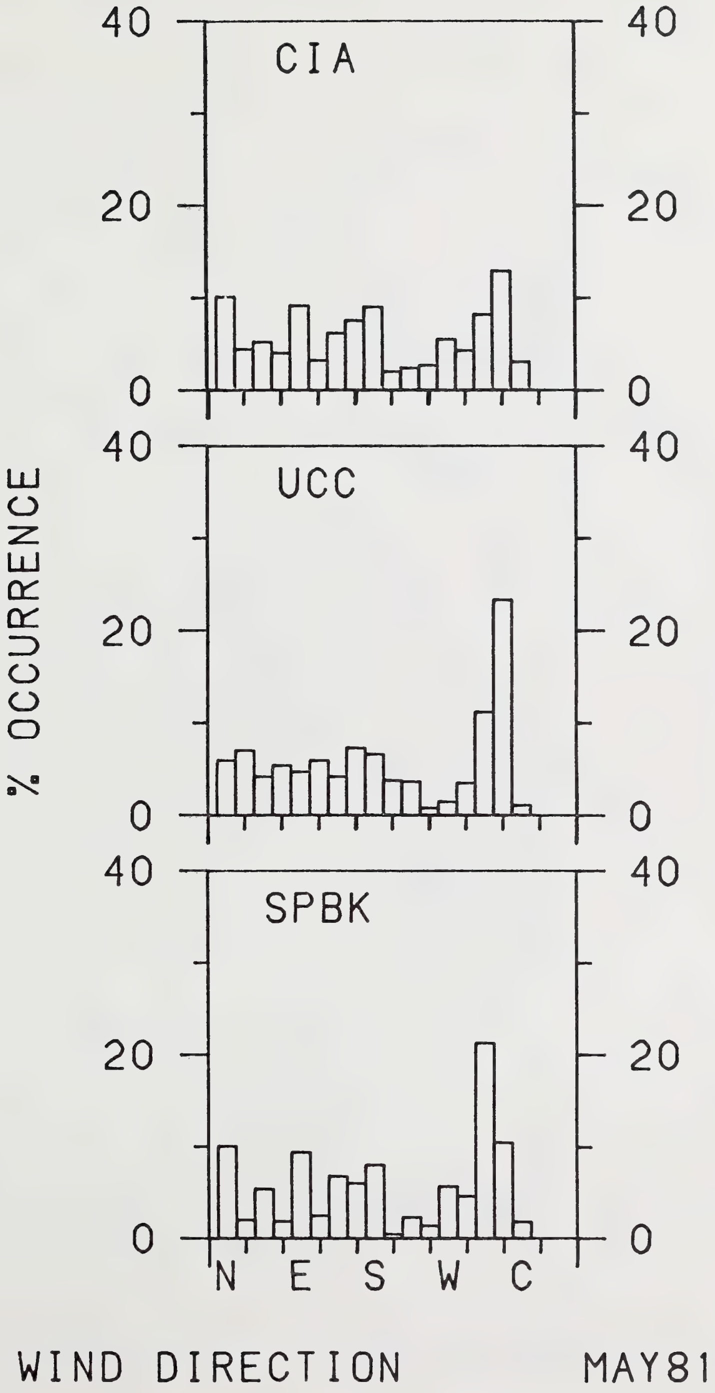

Figure 35. Distributions of surface wind directions for the month of May 1981.

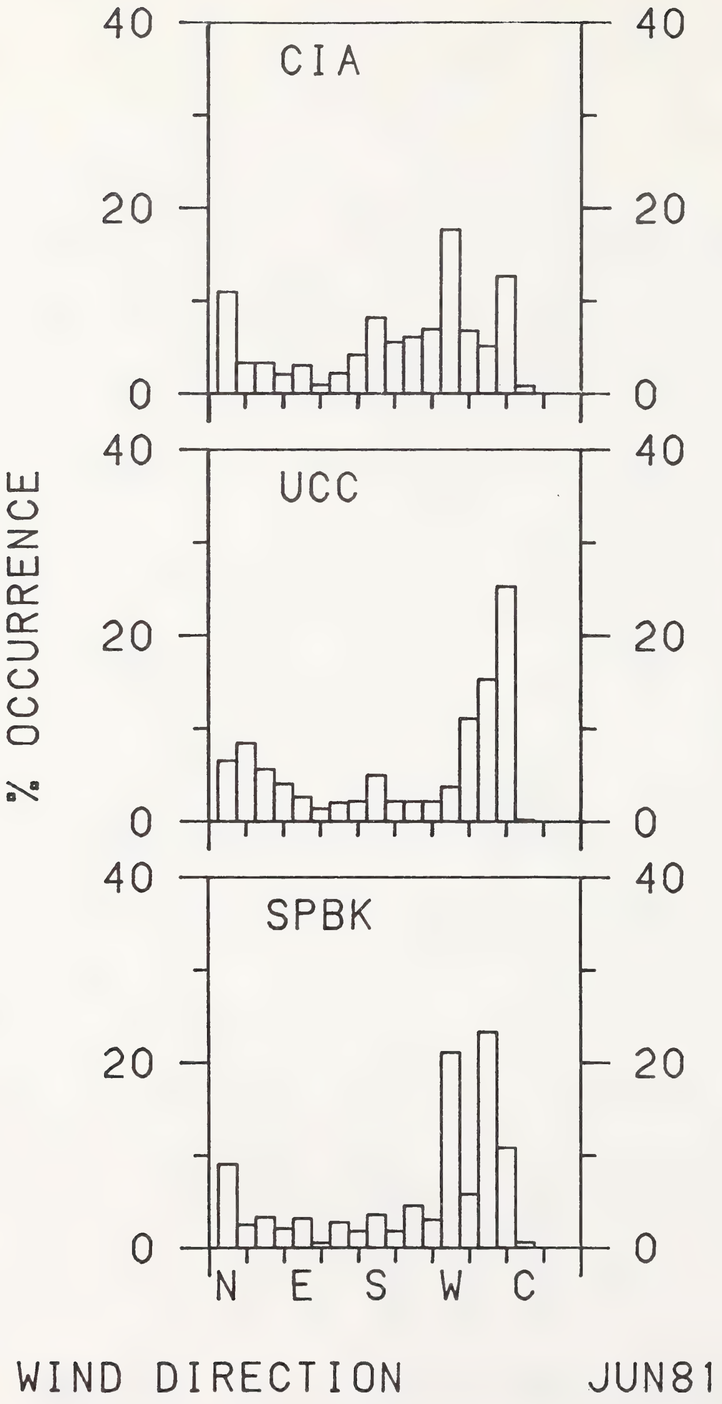

Figure 36. Distributions of surface wind directions for the month of June 1981.

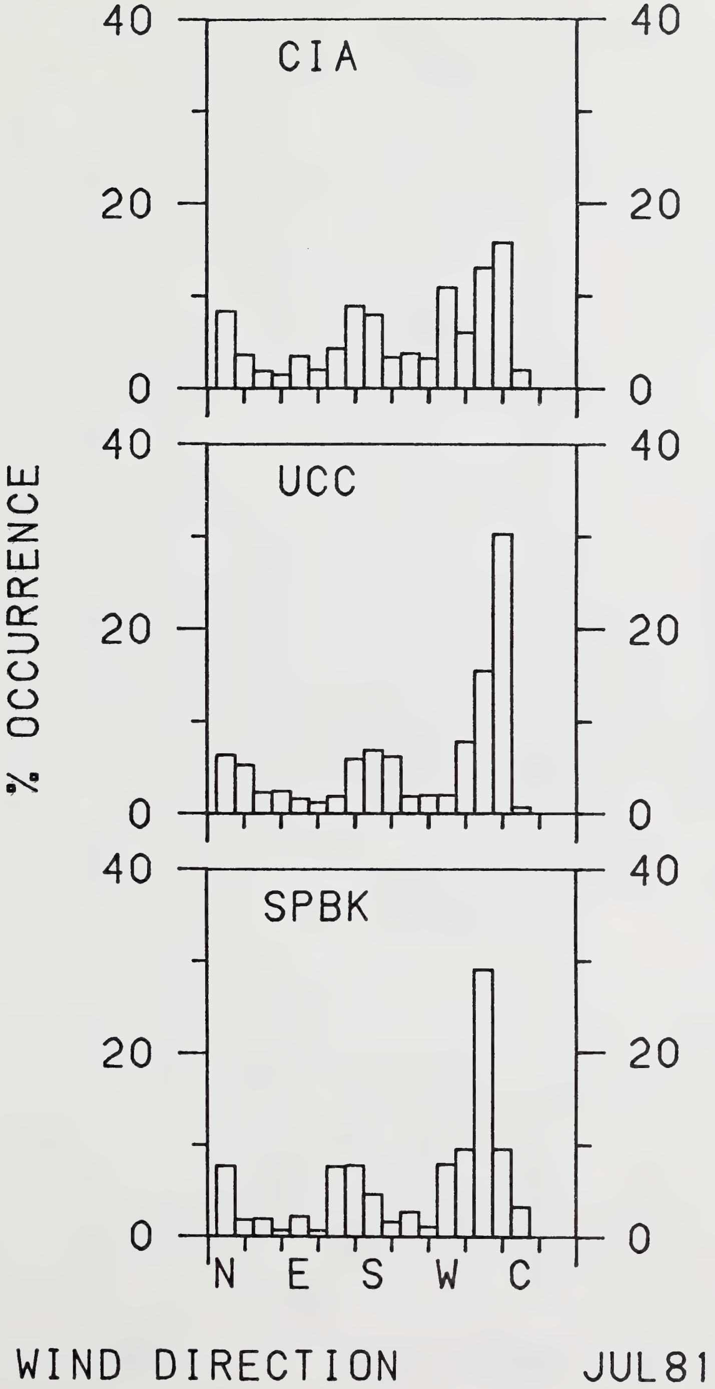

Figure 37. Distributions of surface wind directions for the month of July 1981.

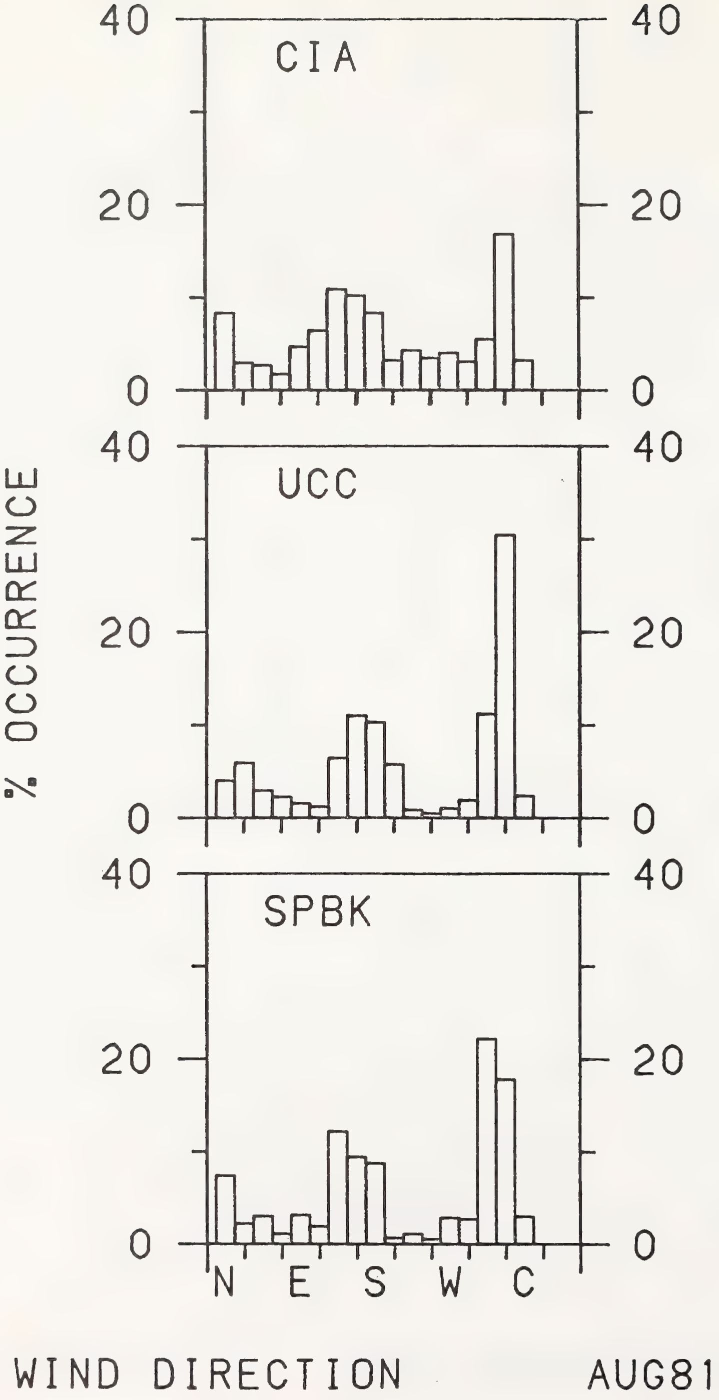

Figure 38. Distributions of surface wind directions for the month of August 1981.

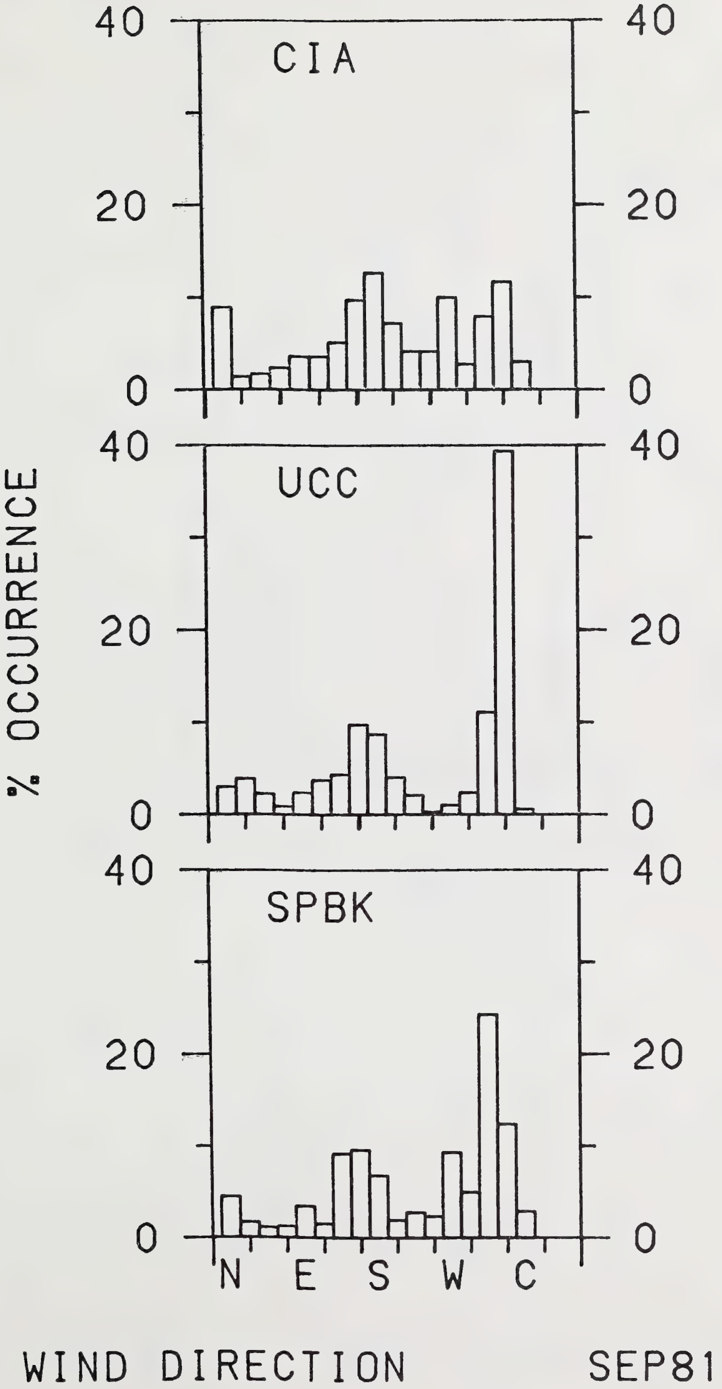

Figure 39. Distributions of surface wind directions for the month of September 1981.

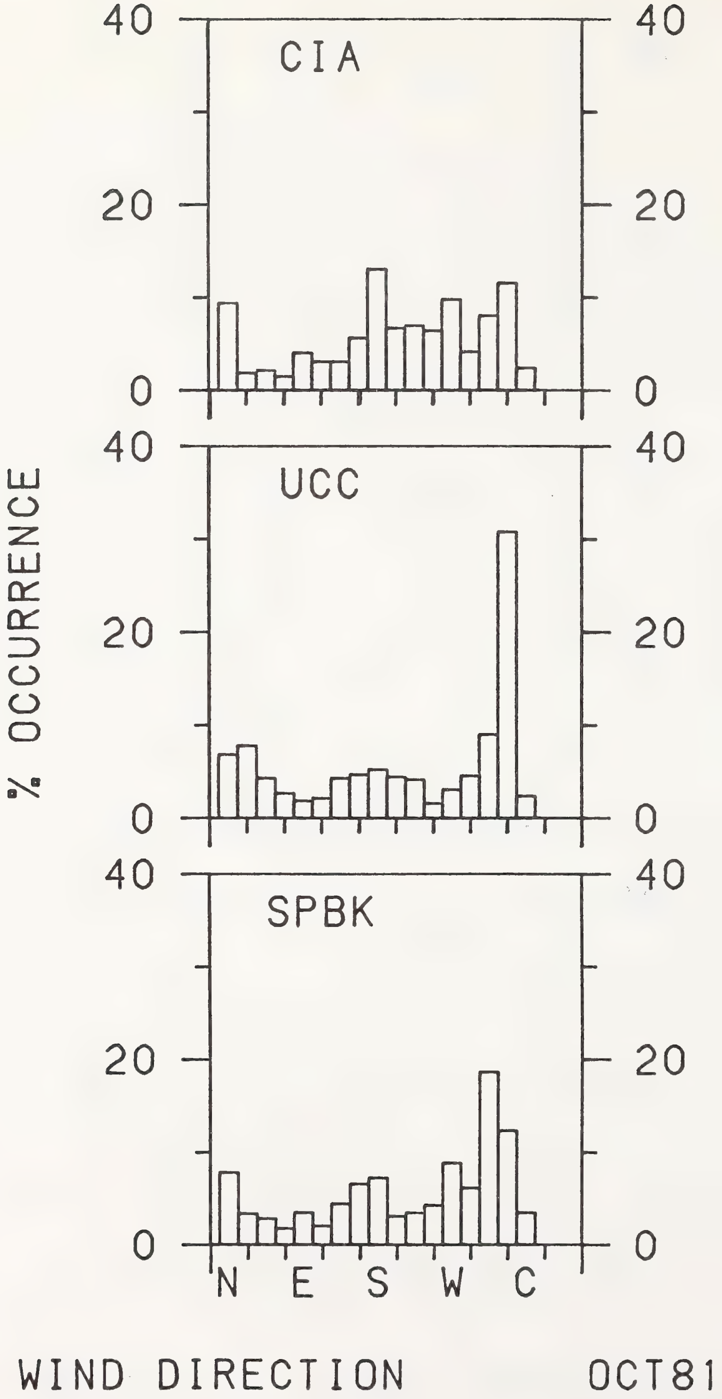

Figure 40. Distributions of surface wind directions for the month of October 1981.

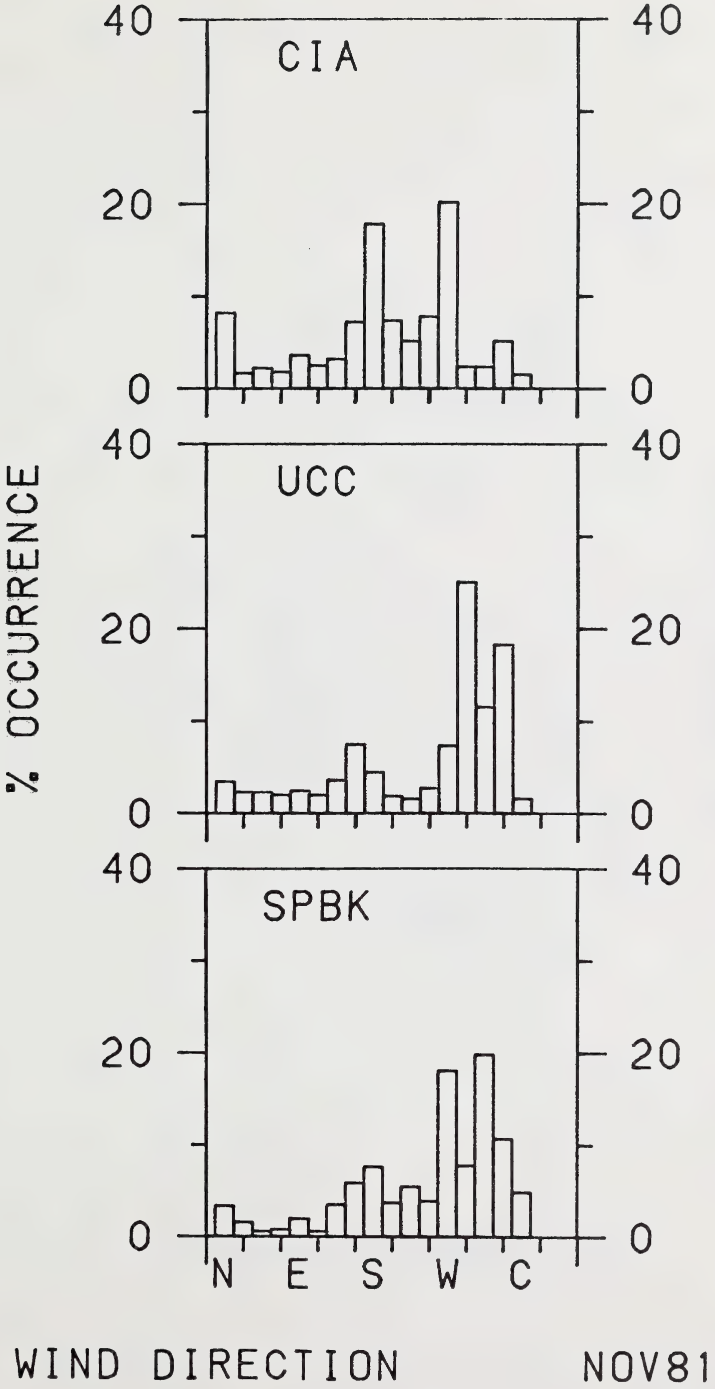

Figure 41. Distributions of surface wind directions for the month of November 1981.

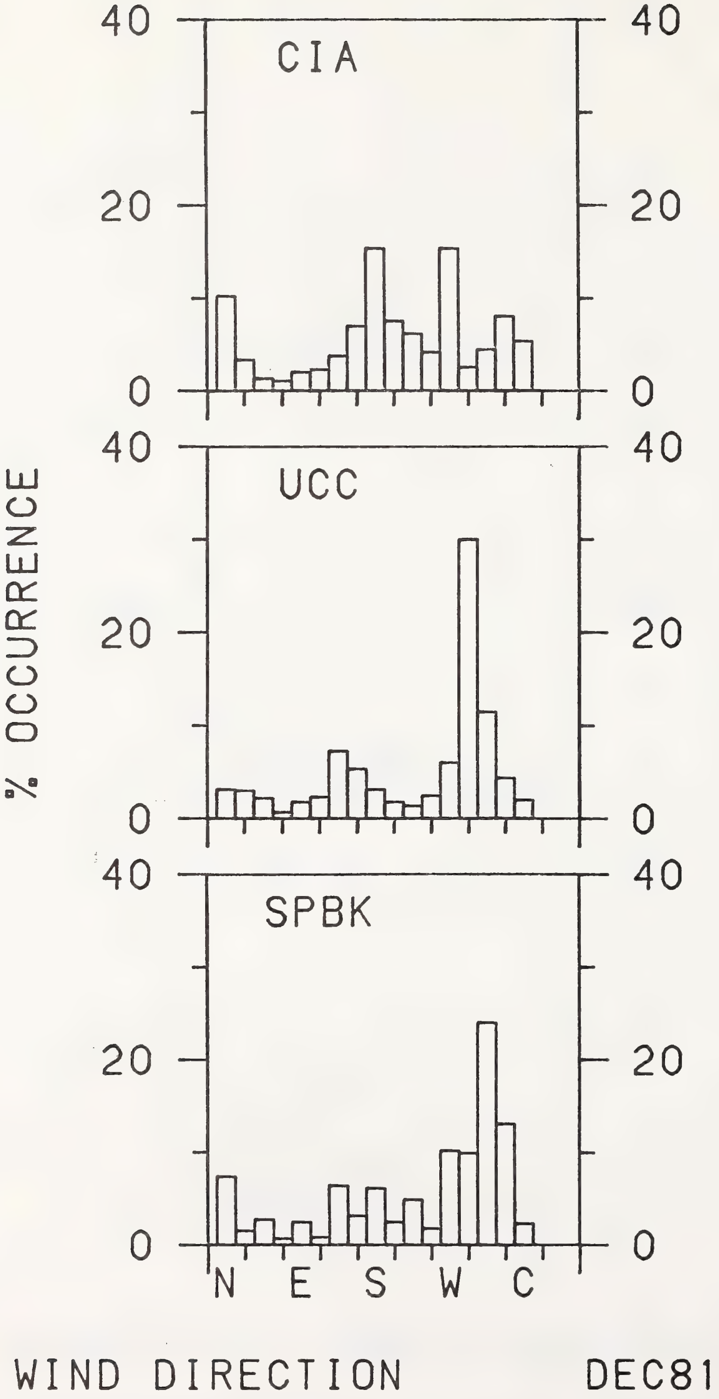

Figure 42. Distributions of surface wind directions for the month of December 1981.

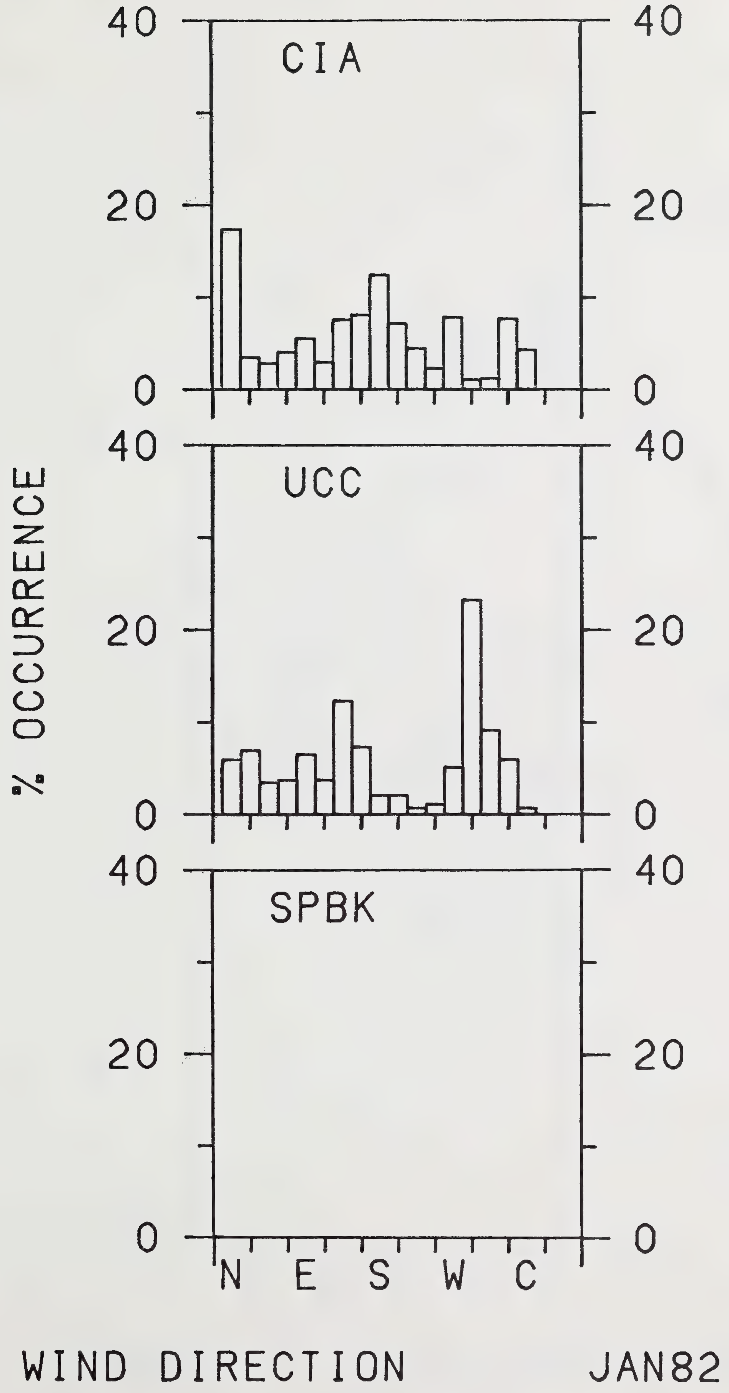

Figure 43. Distributions of surface wind directions for the month of January 1982.

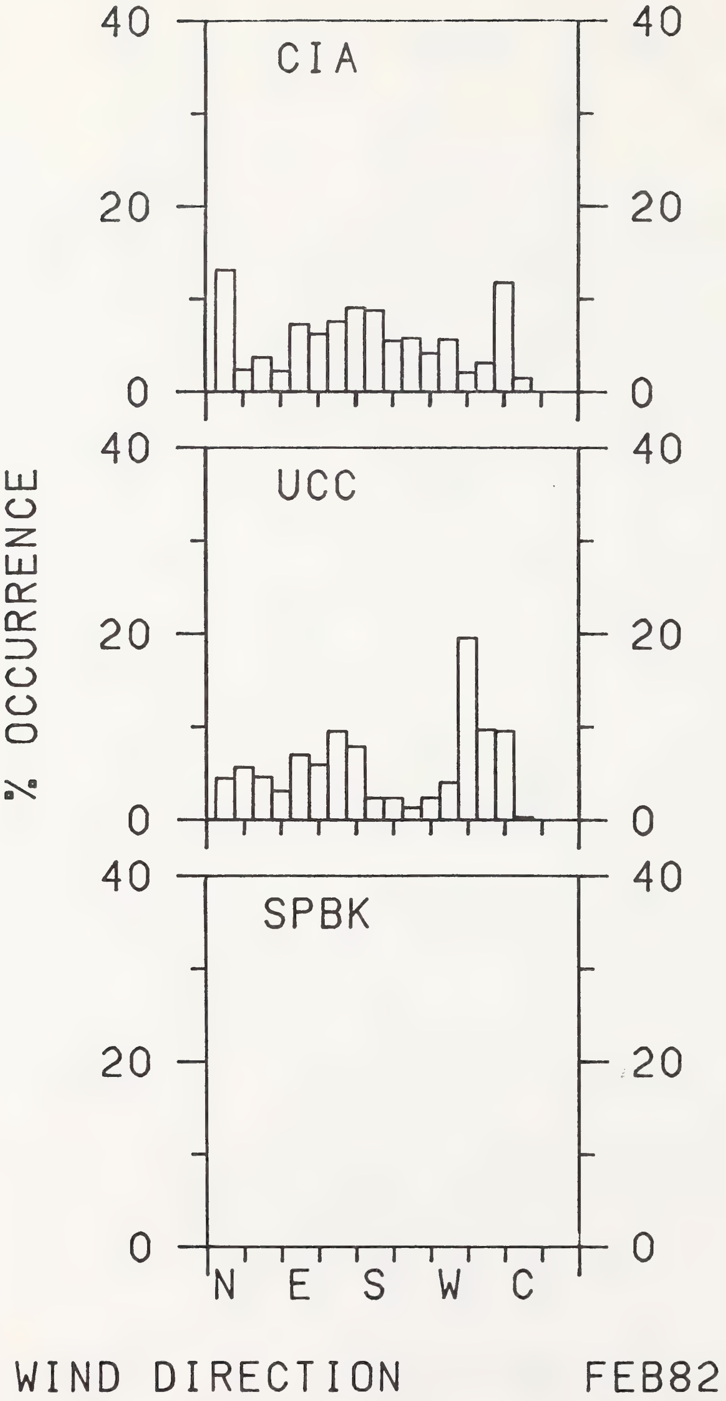

Figure 44. Distributions of surface wind directions for the month of February 1982.

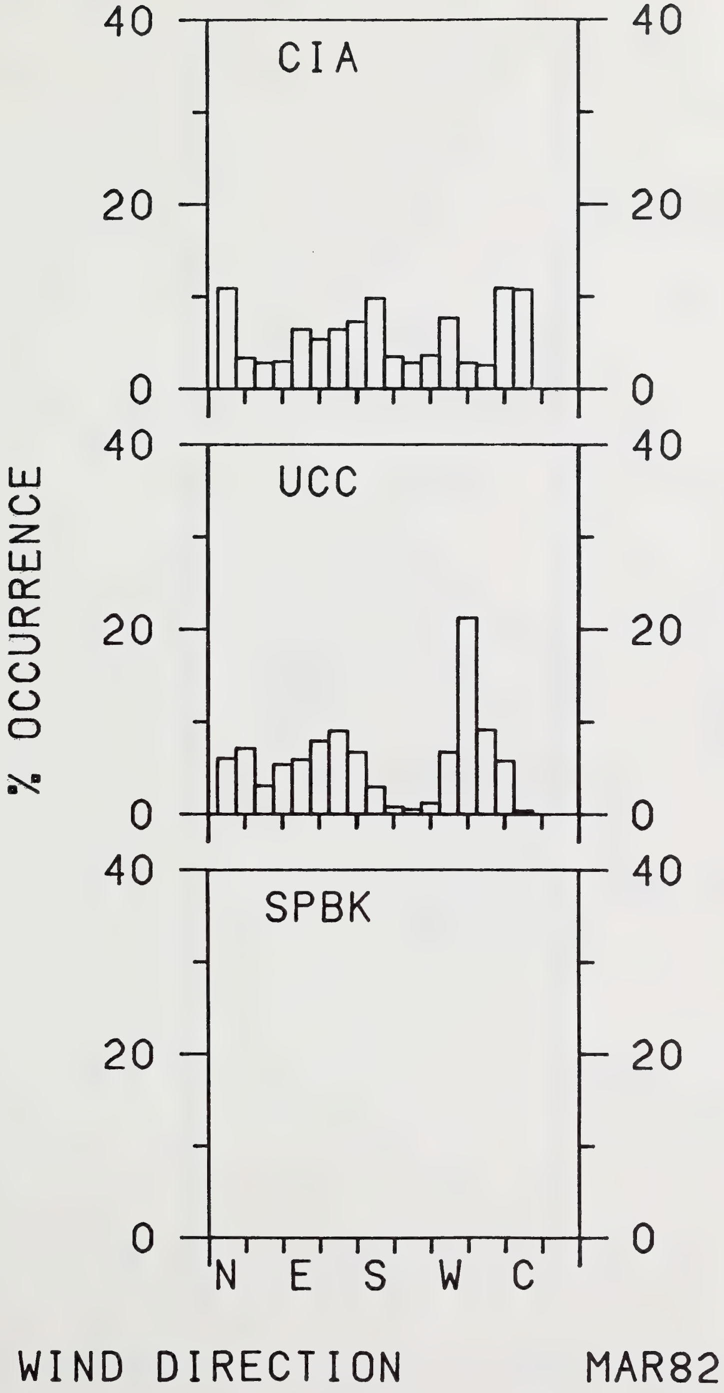

Figure 45. Distributions of surface wind directions for the month of March 1982.

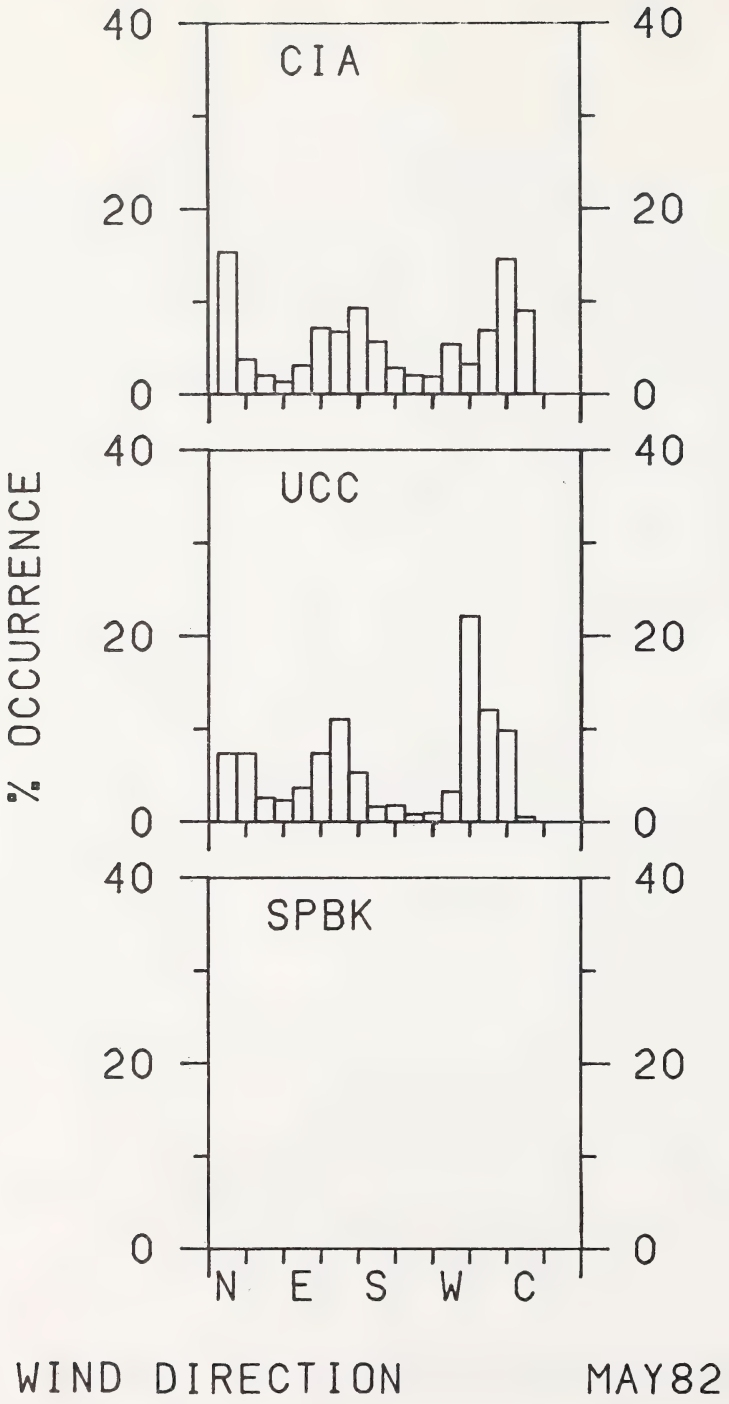

Figure 46. Distributions of surface wind directions for the month of May 1982.

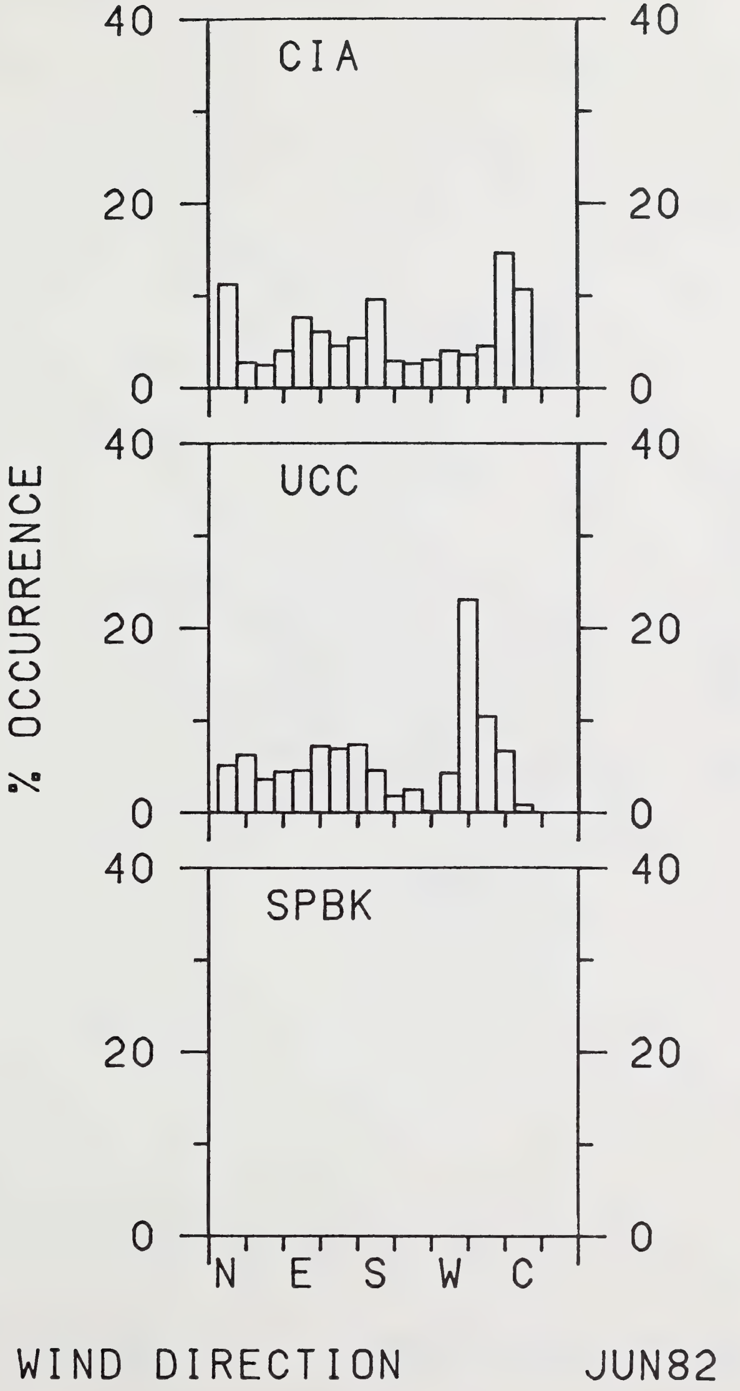

Figure 47. Distributions of surface wind directions for the month of June 1982.

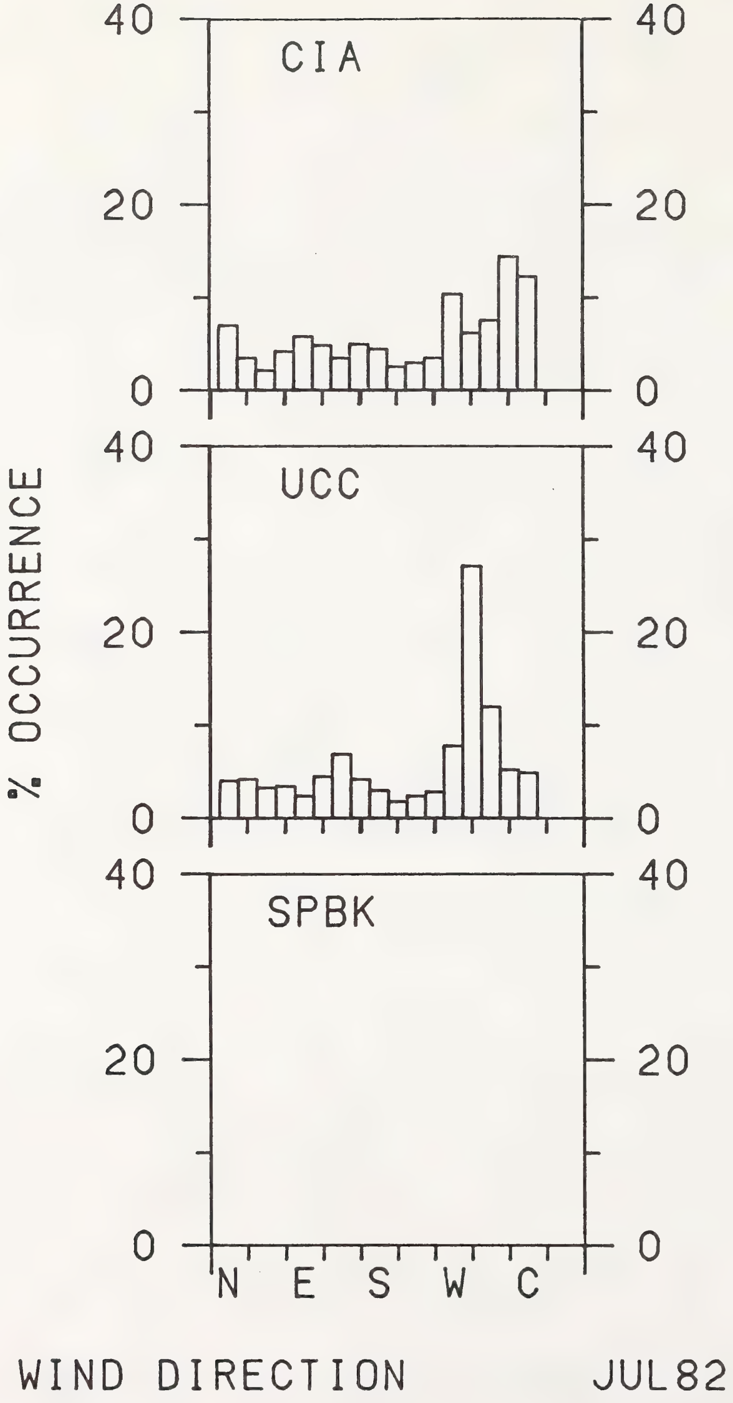

Figure 48. Distributions of surface wind directions for the month of July 1982.

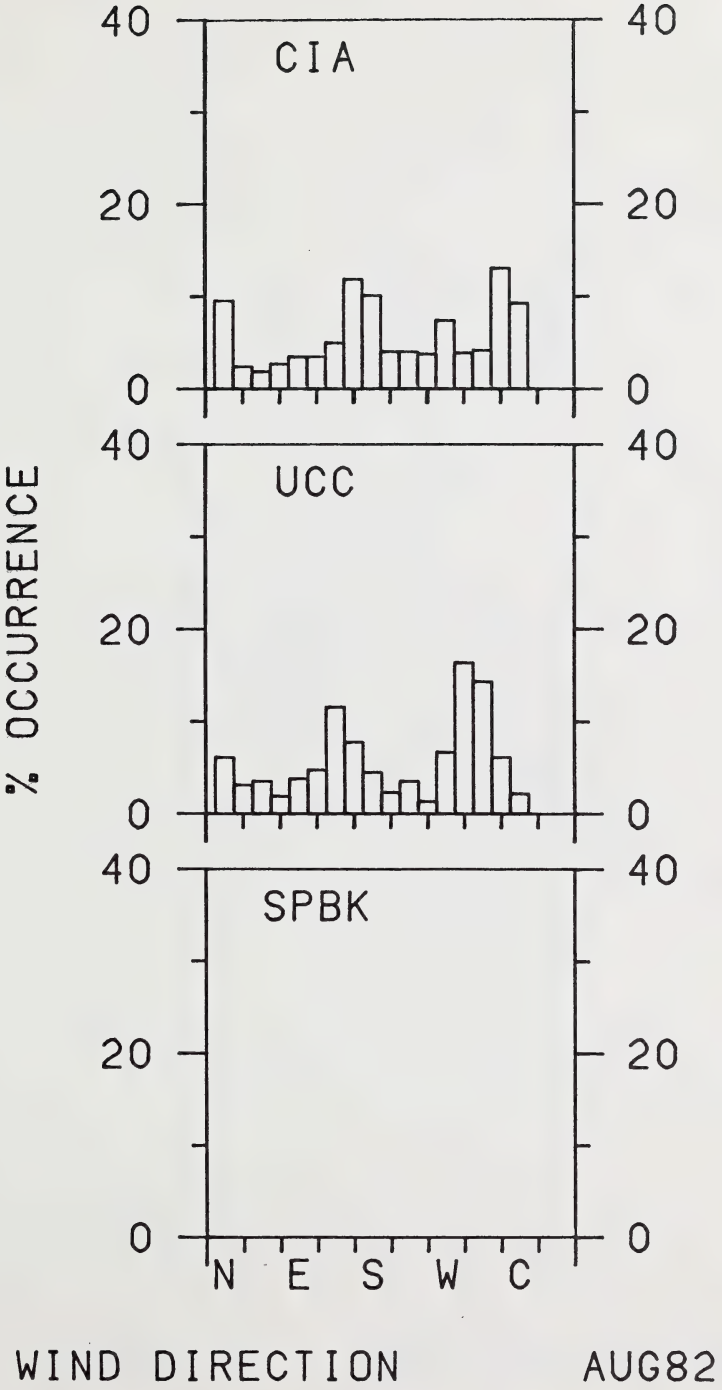

Figure 49. Distributions of surface wind directions for the month of August 1982.

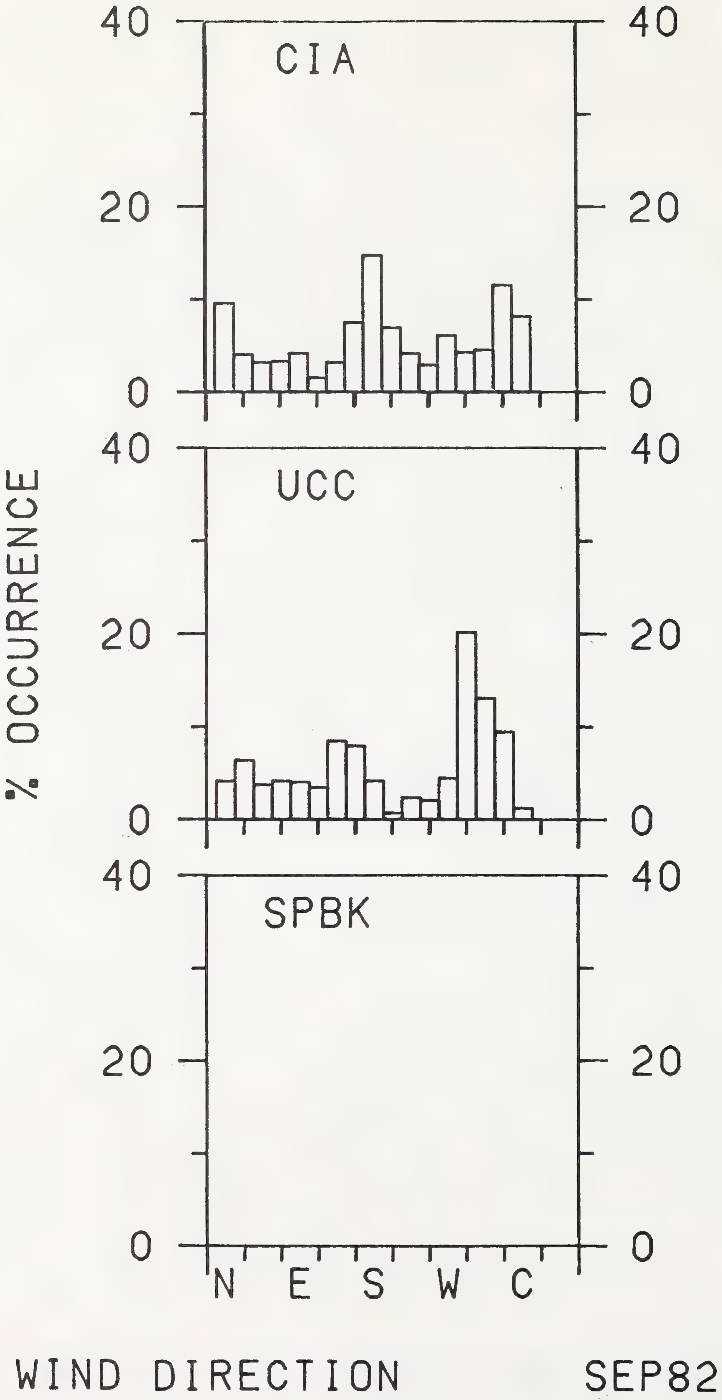

Figure 50. Distributions of surface wind directions for the month of September 1982.

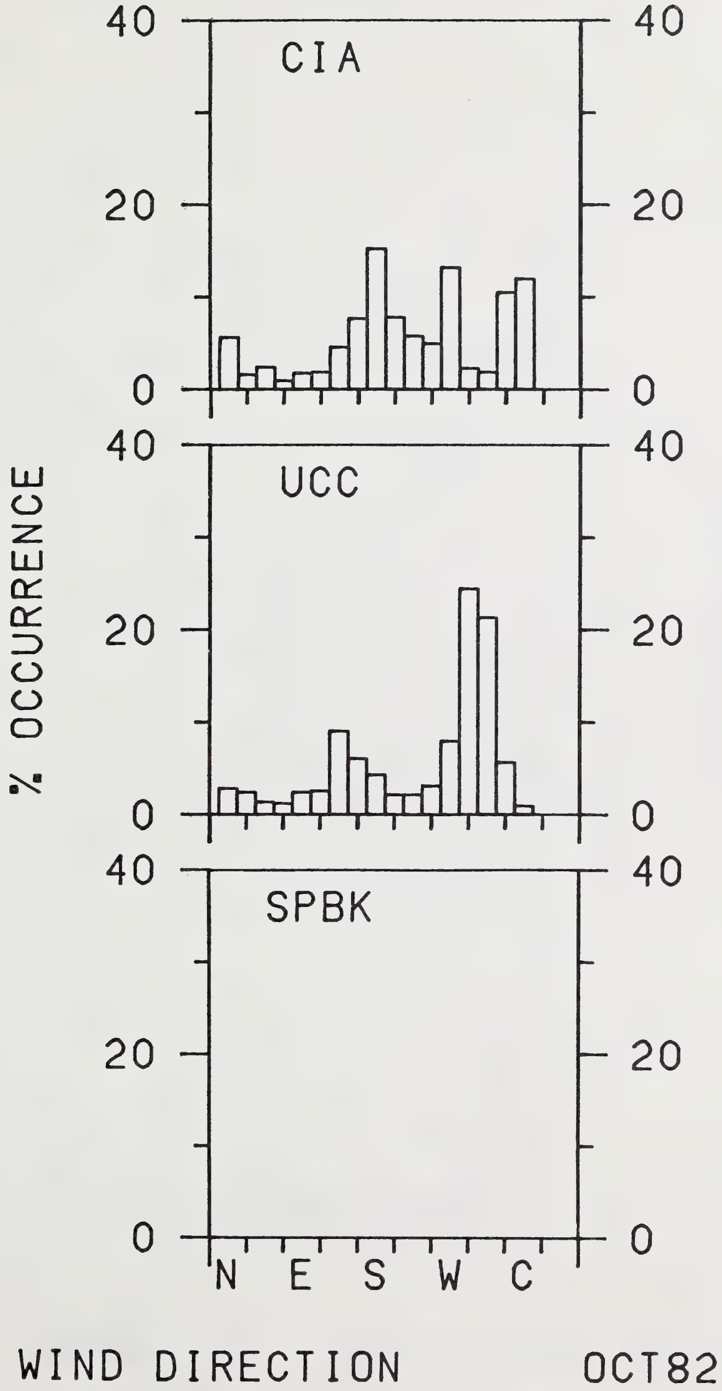

Figure 51. Distributions of surface wind directions for the month of October 1982.

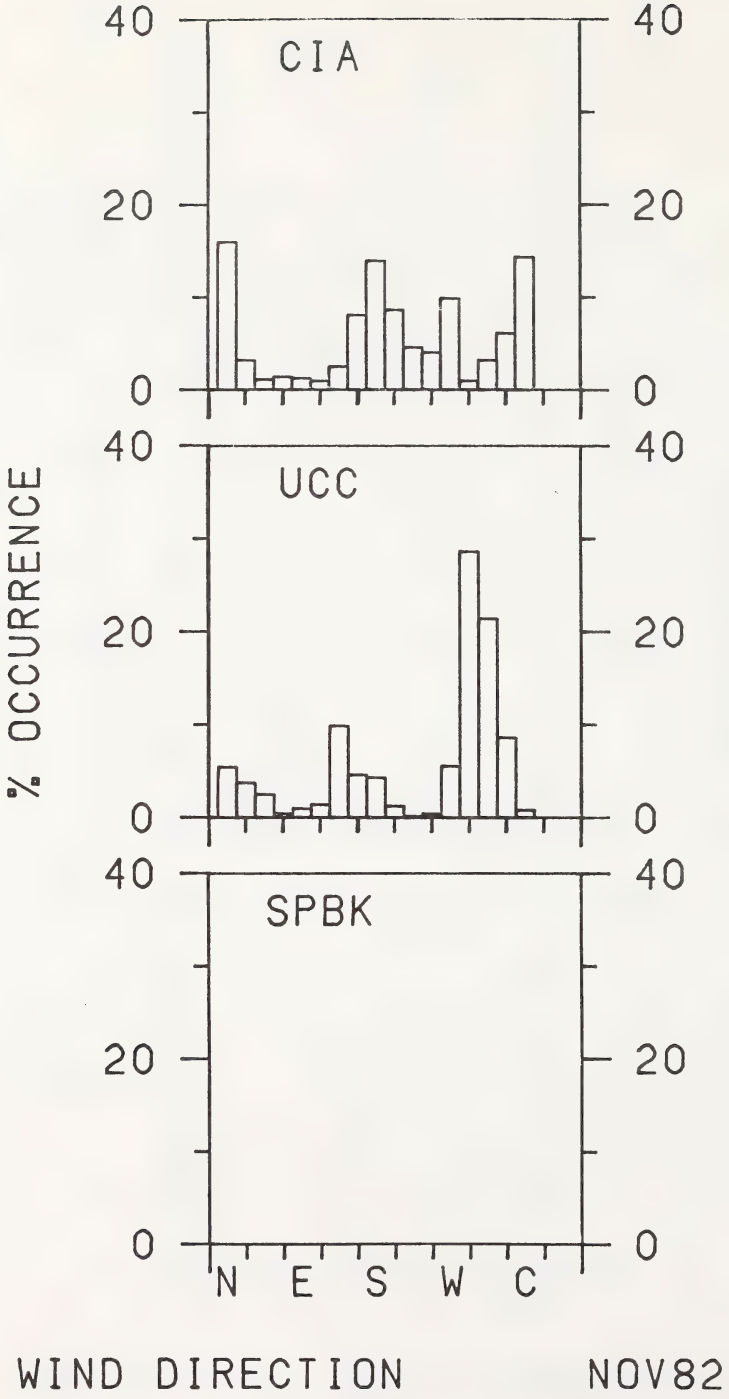

Figure 52. Distributions of surface wind directions for the month of November 1982.

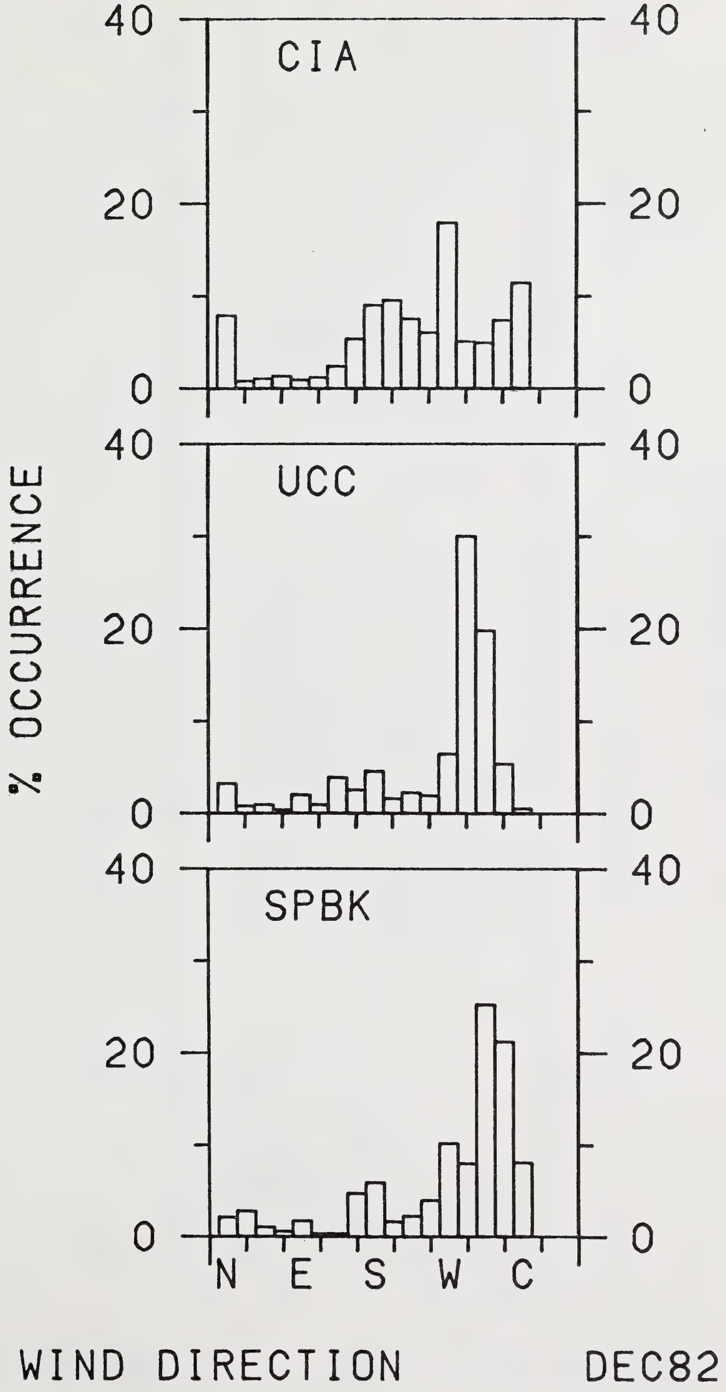

Figure 53. Distributions of surface wind directions for the month of December 1982.

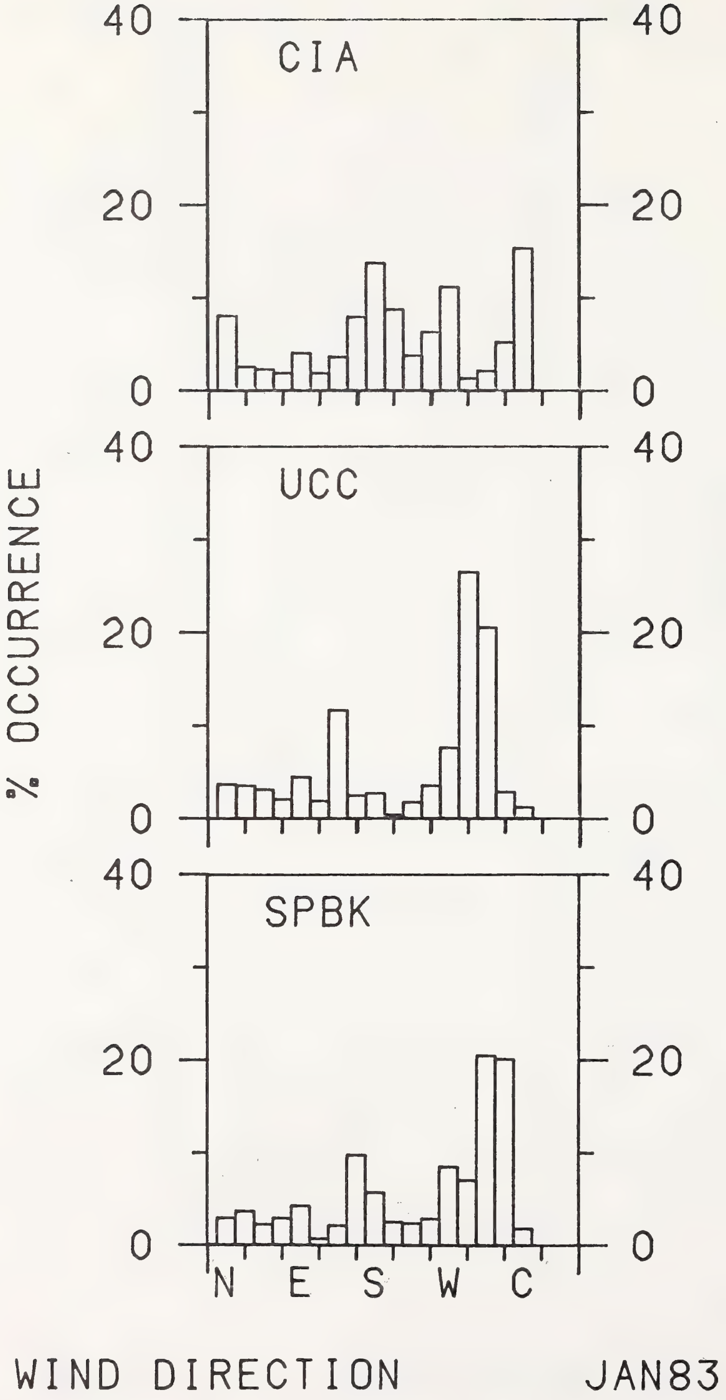

Figure 54. Distributions of surface wind directions for the month of January 1983.

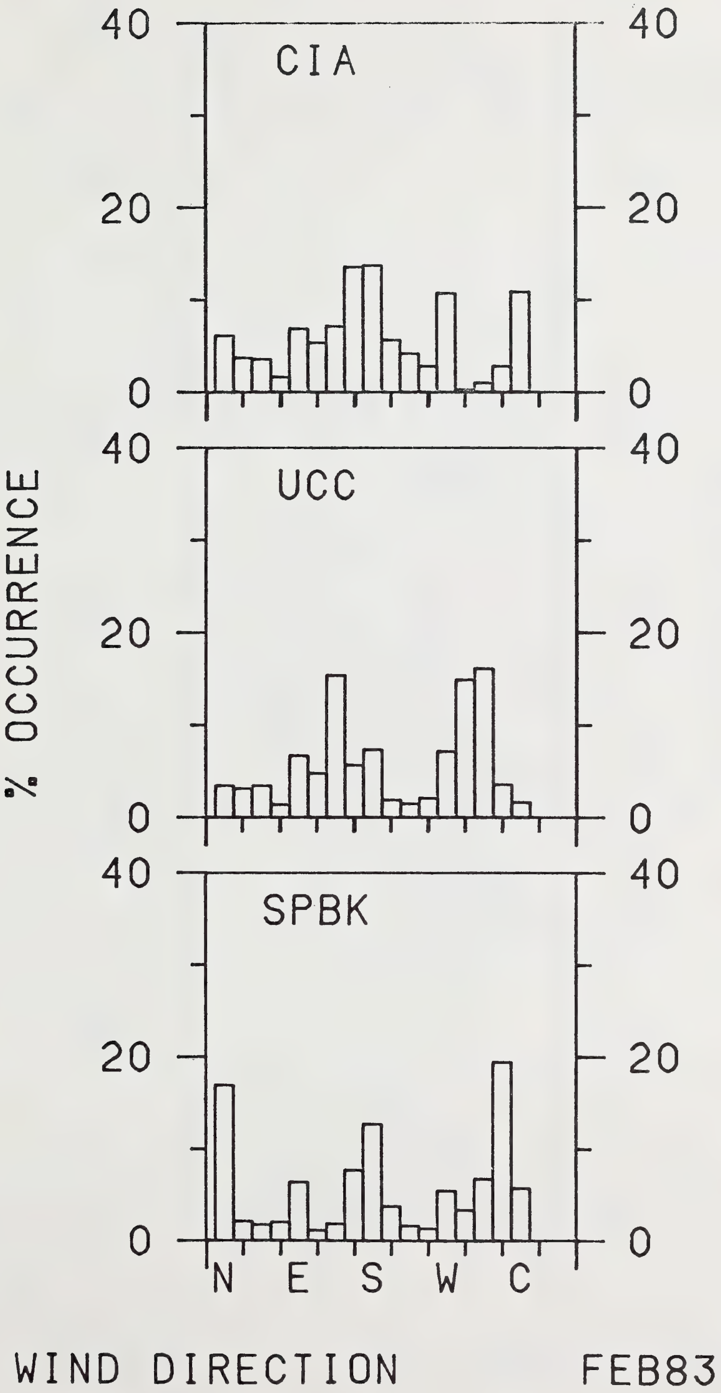

Figure 55. Distributions of surface wind directions for the month of February 1983.

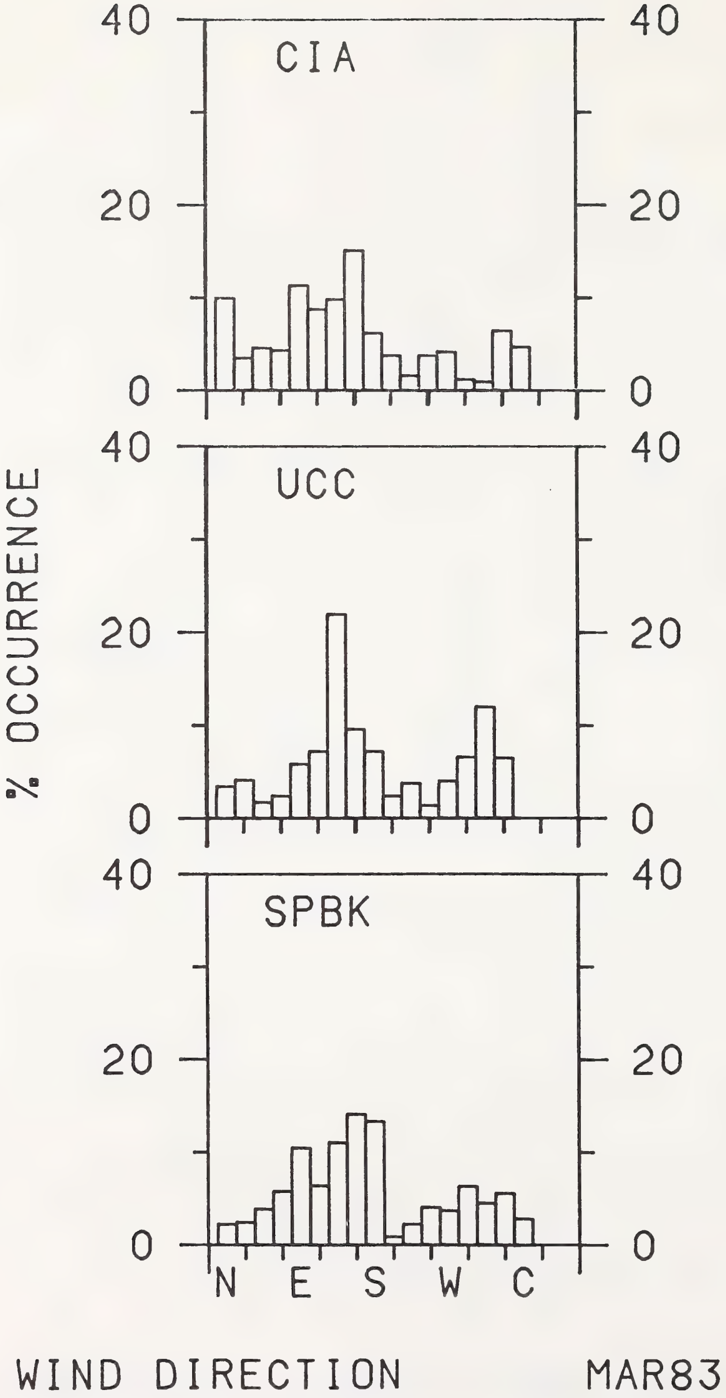

Figure 56. Distributions of surface wind directions for the month of March 1983.

8.4 DOPPLER WIND DISTRIBUTIONS

The following figures show monthly distributions of Doppler wind directions for the period November 1980 to March 1983.

Directions

N = north
E = east
S = south
W = west
C = calm

The height above ground level is given on each plot (e.g., 100 m, 150 m, etc.)

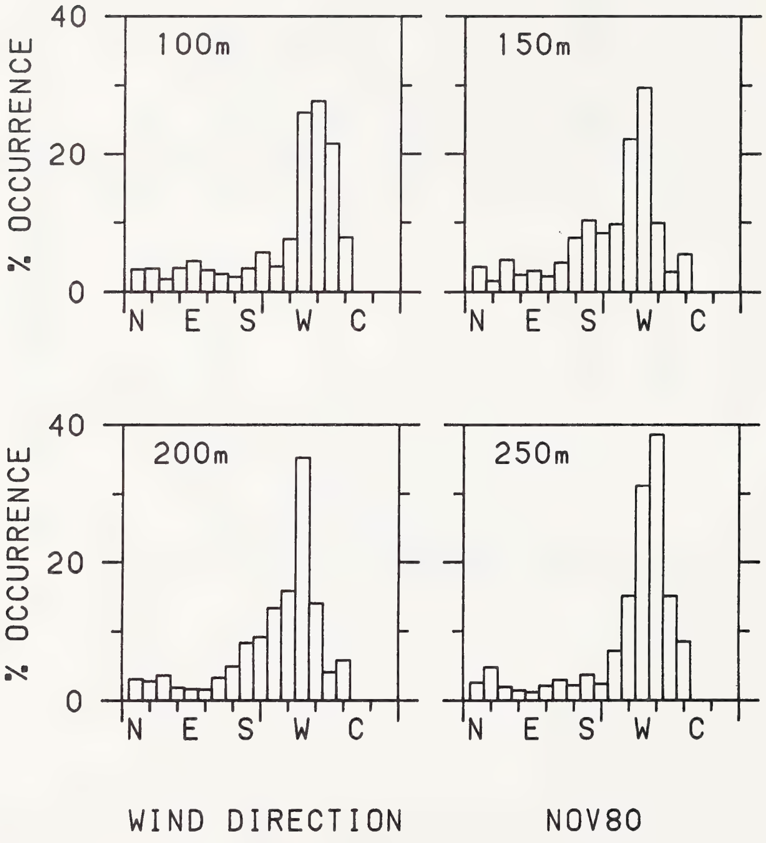

Figure 57. Distributions of Doppler wind directions for the month of November 1980.

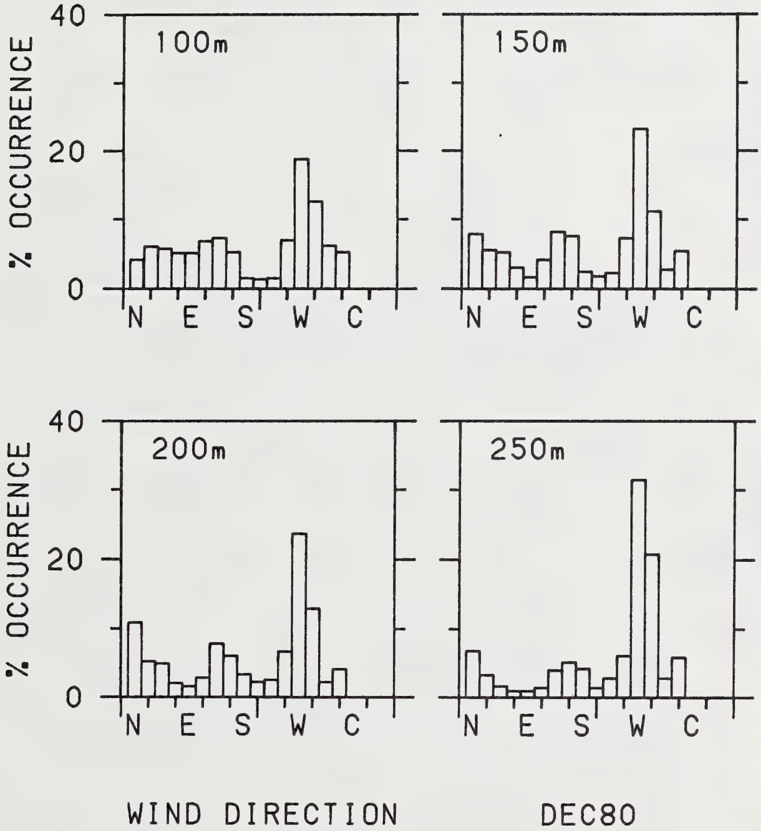

Figure 58. Distributions of Doppler wind directions for the month of December.

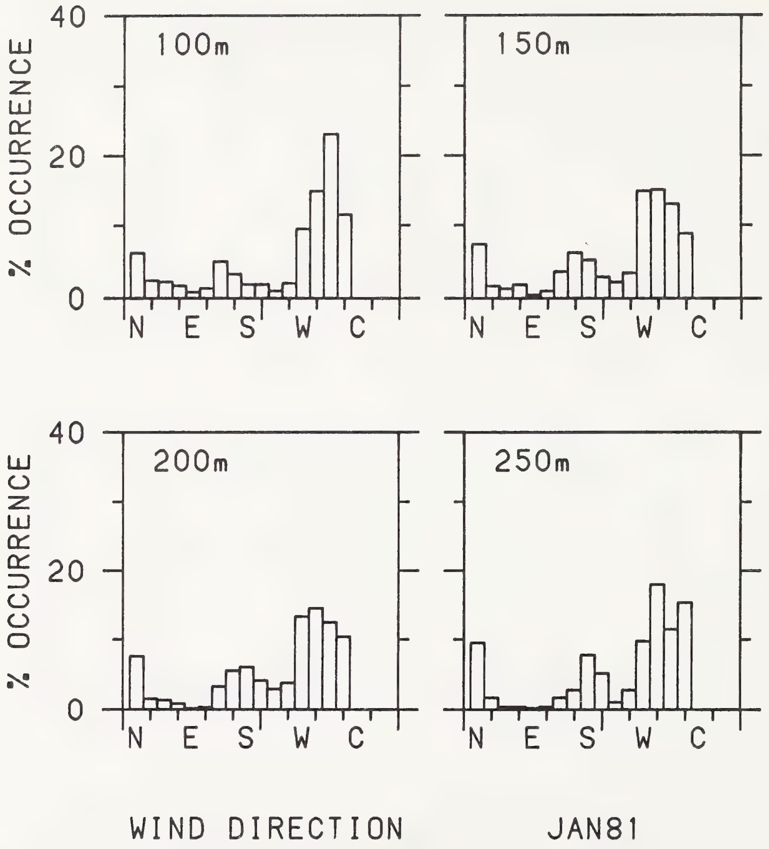

Figure 59. Distributions of Doppler wind directions for the month of January 1981.

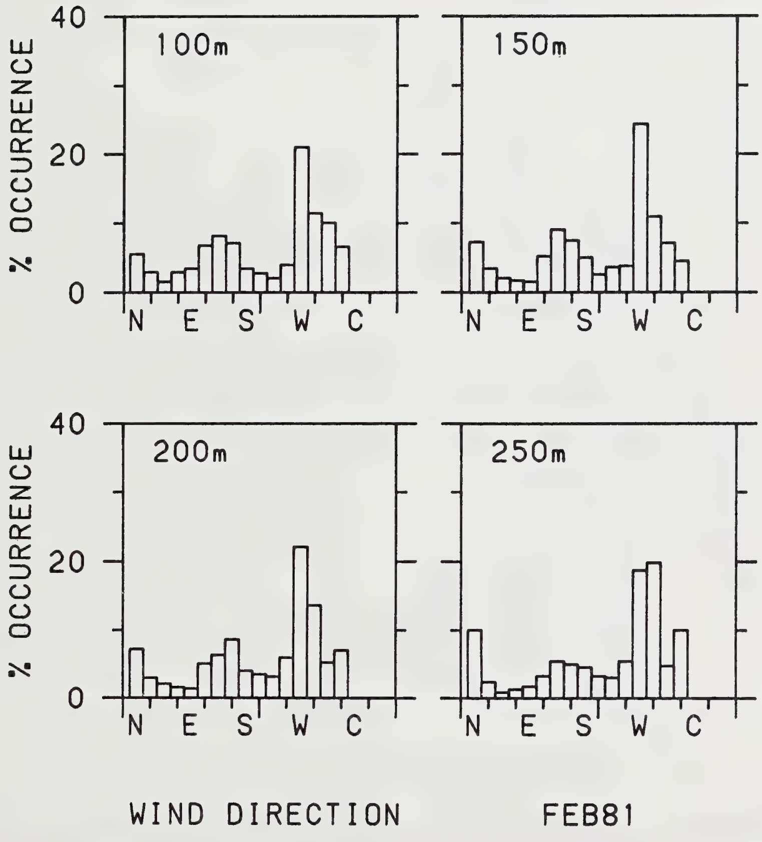

Figure 60. Distributions of Doppler wind directions for the month of February 1981.

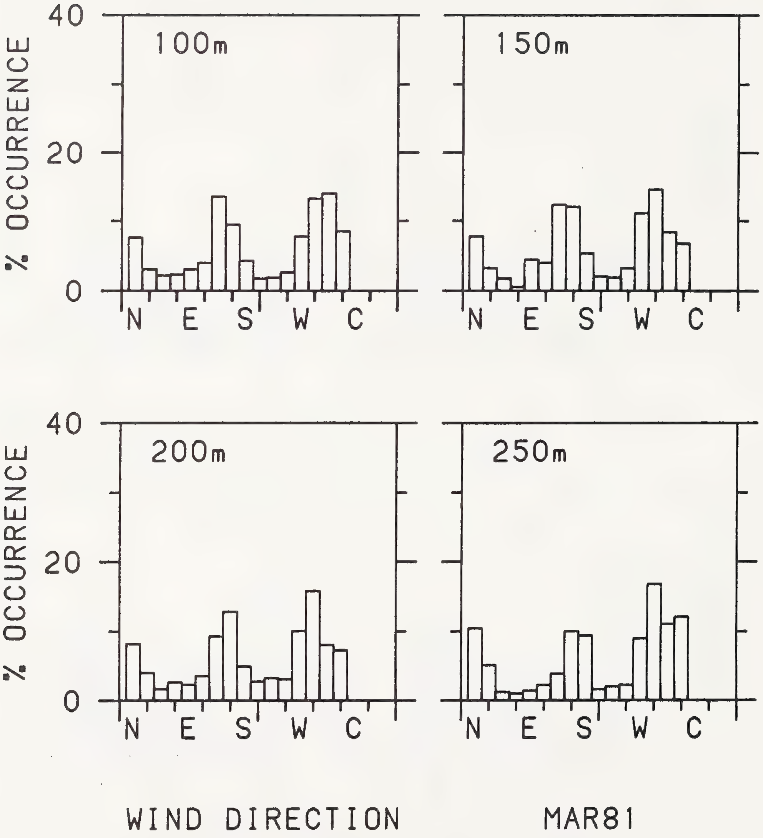

Figure 61. Distributions of Doppler wind directions for the month of March 1981.

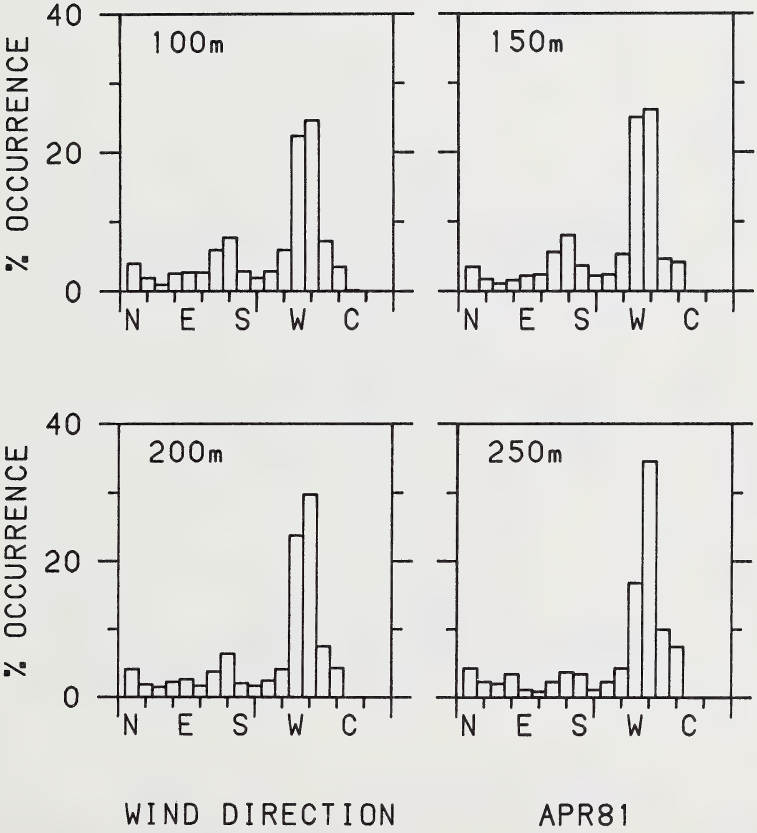

Figure 62. Distributions of Doppler wind directions for the month of April 1981.

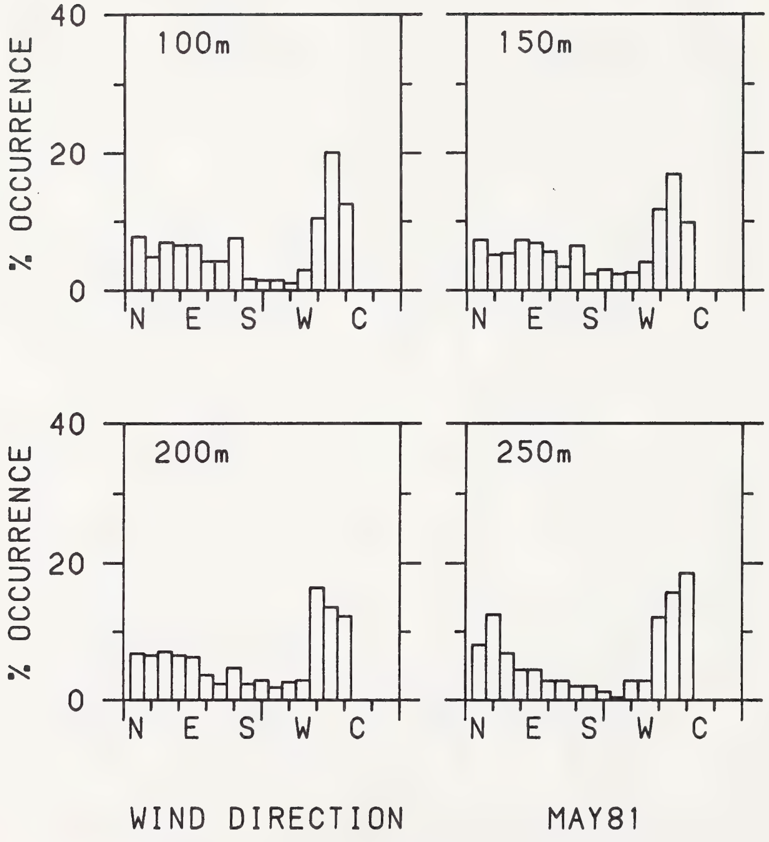

Figure 63. Distributions of Doppler wind directions for the month of May 1981.

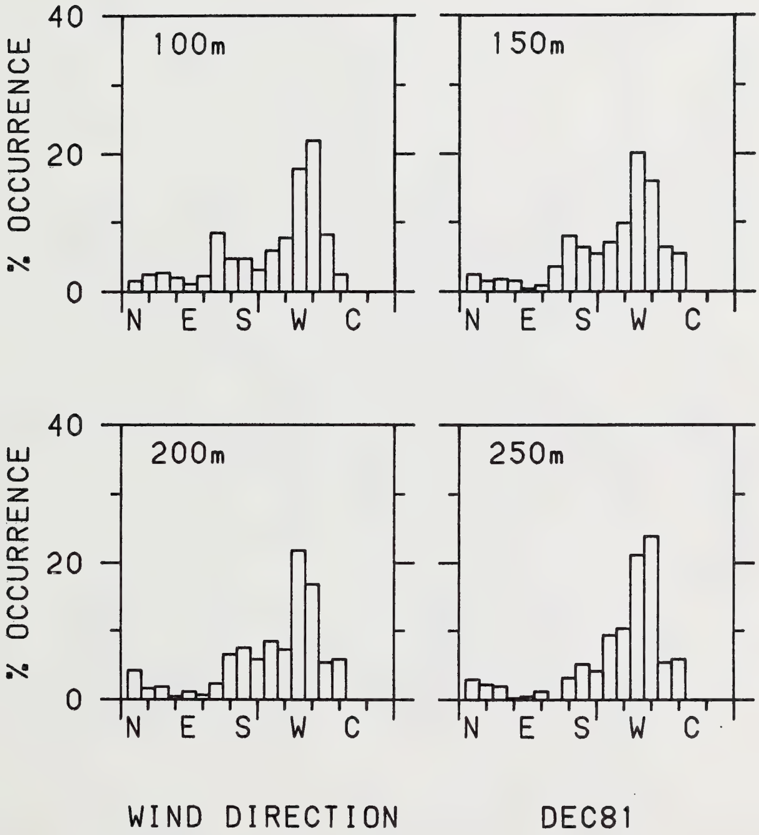

Figure 64. Distributions of Doppler wind directions for the month of December 1981.

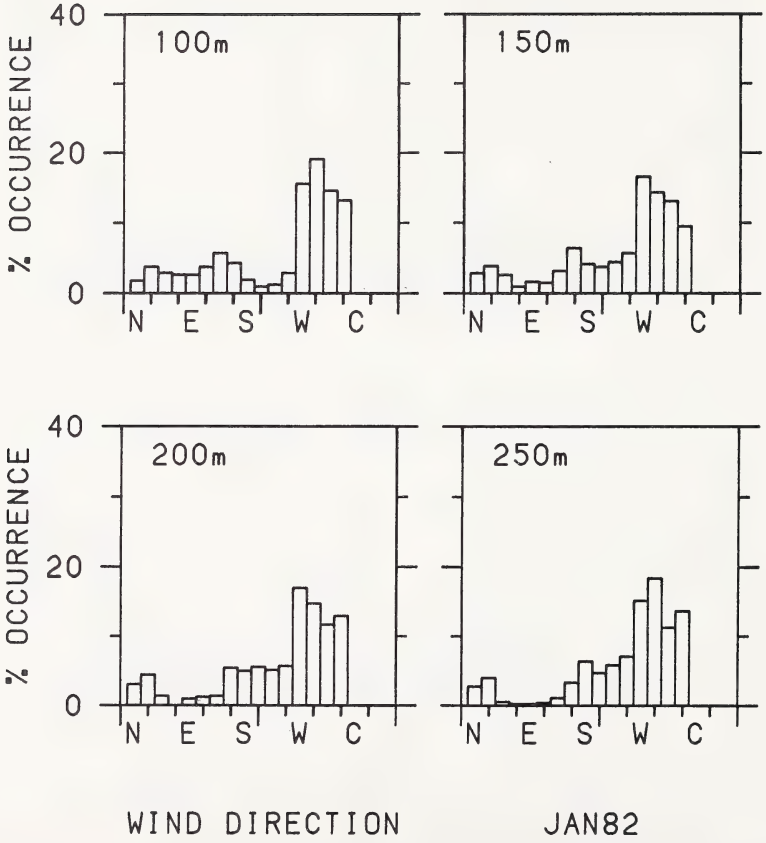

Figure 65. Distributions of Doppler wind directions for the month of January 1982.

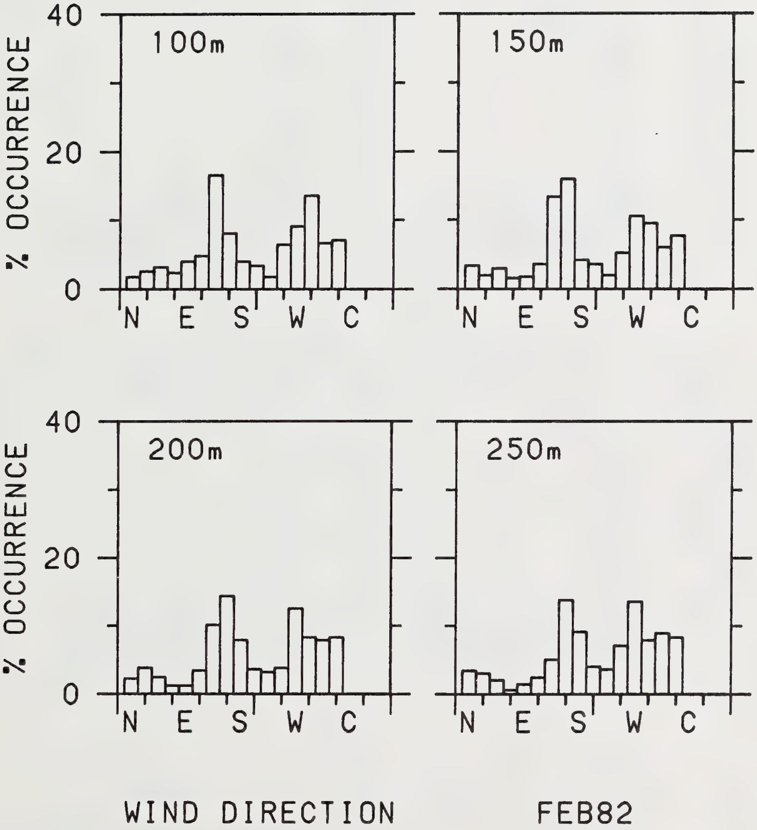

Figure 66. Distributions of Doppler wind directions for the month of February 1982.

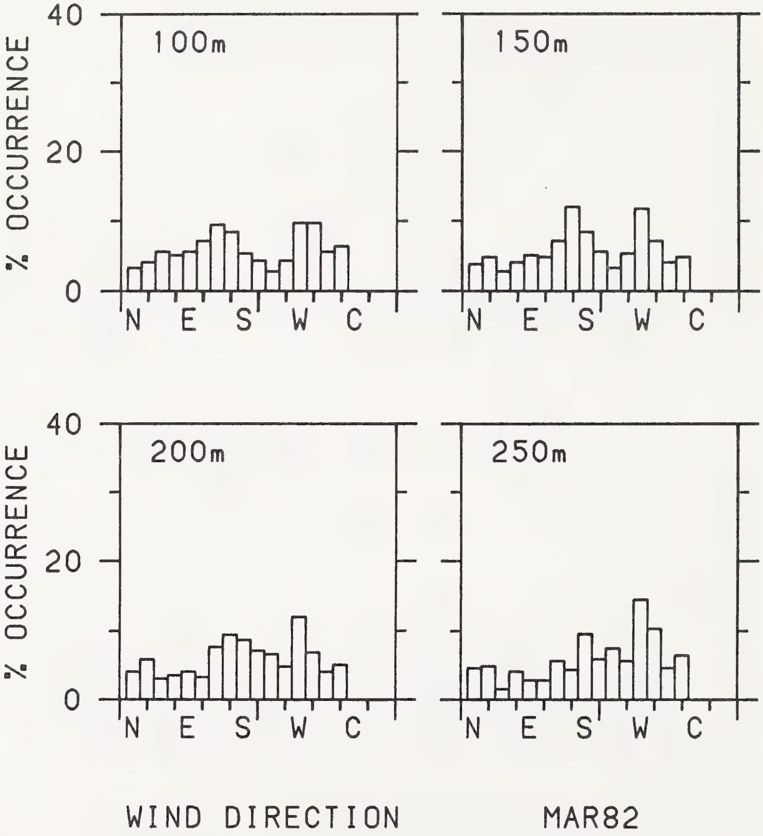

Figure 67. Distributions of Doppler wind directions for the month of March 1982.

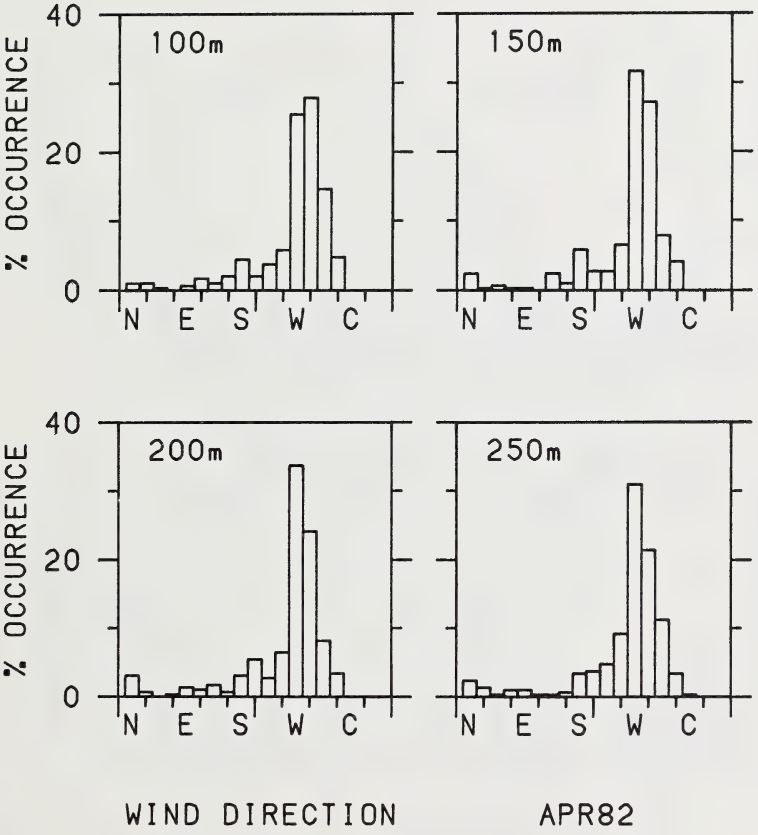

Figure 68. Distributions of Doppler wind directions for the month of April 1982.

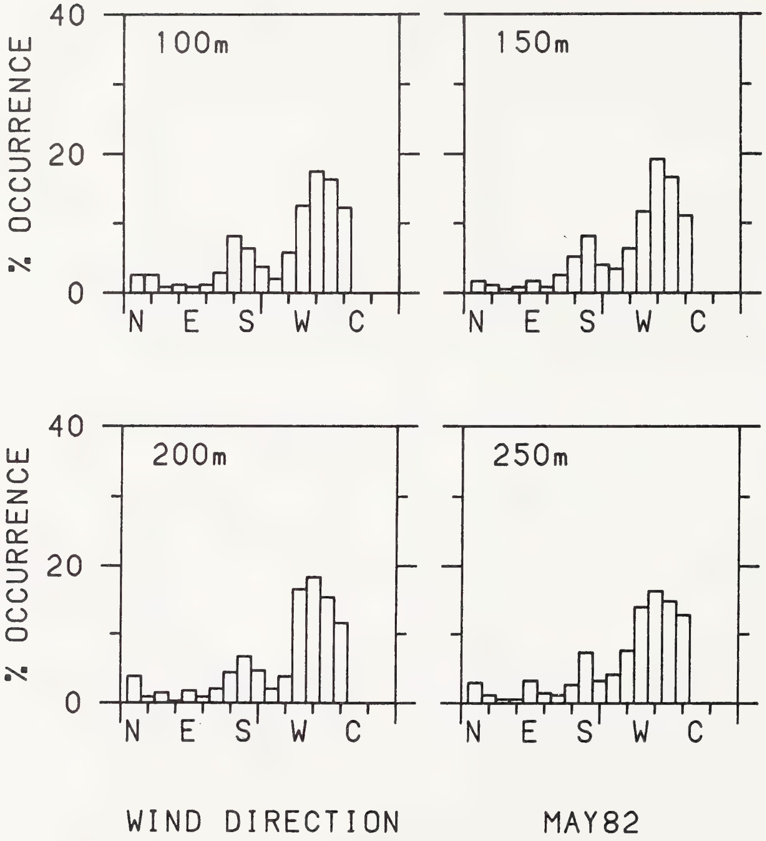

Figure 69. Distributions of Doppler wind directions for the month of May.

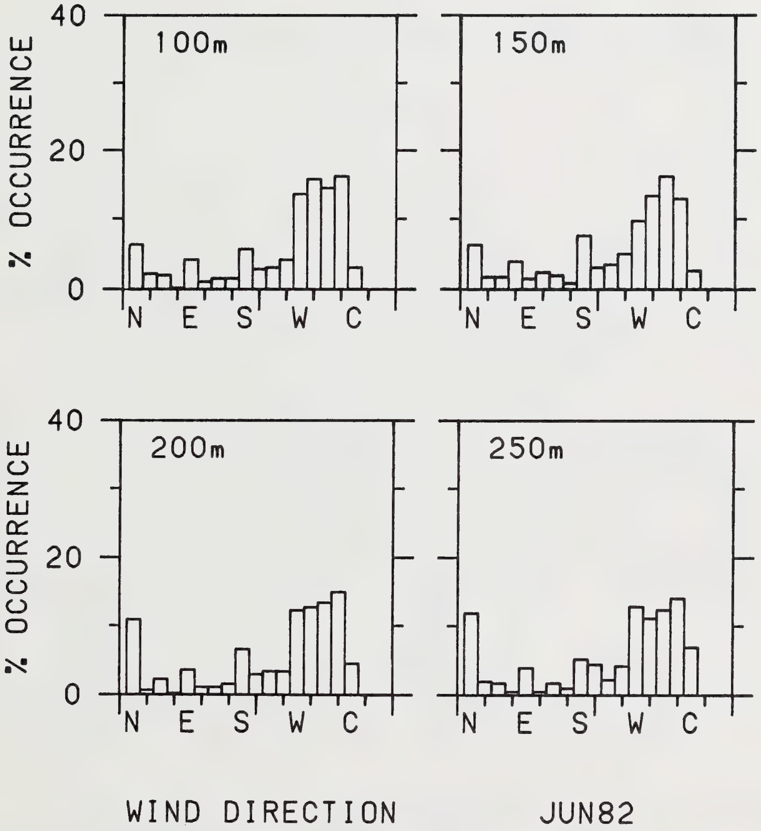

Figure 70. Distributions of Doppler wind directions for the month of June 1982.

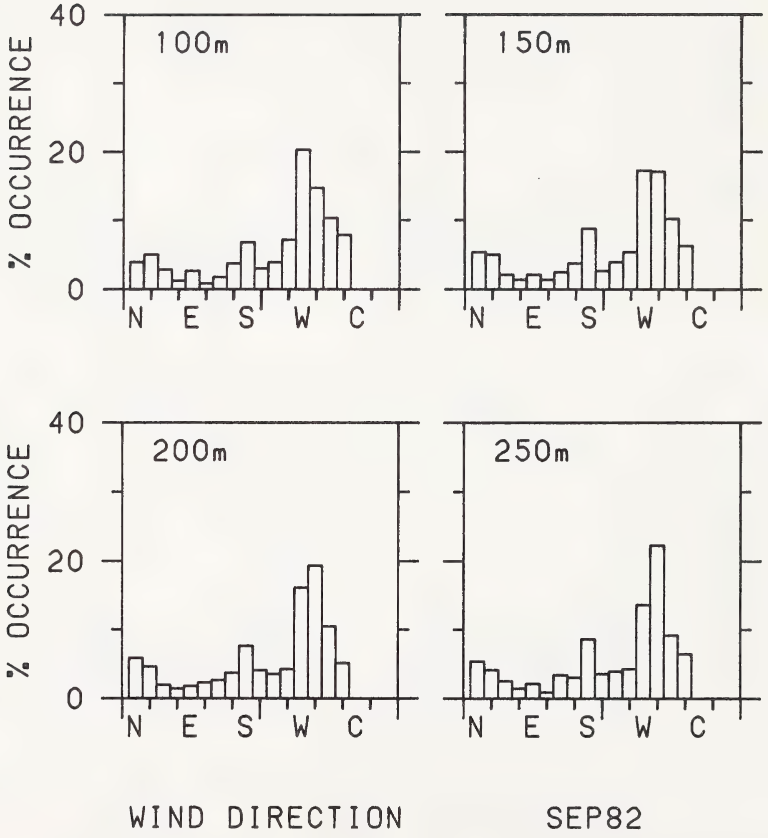

Figure 71. Distributions of Doppler wind directions for the month of September 1982.

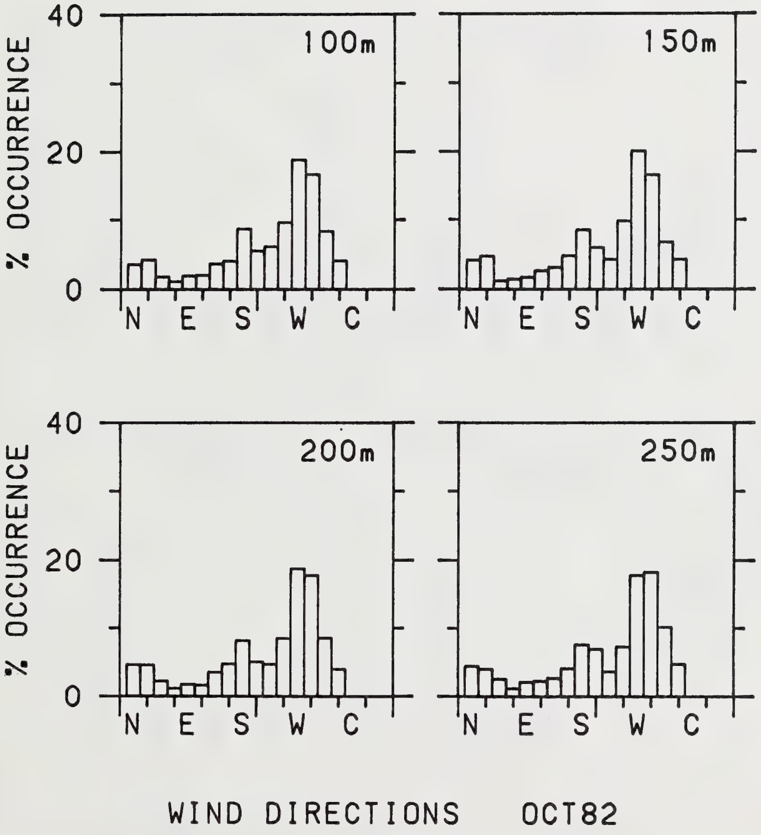

Figure 72. Distributions of Doppler wind directions for the month of October 1982.

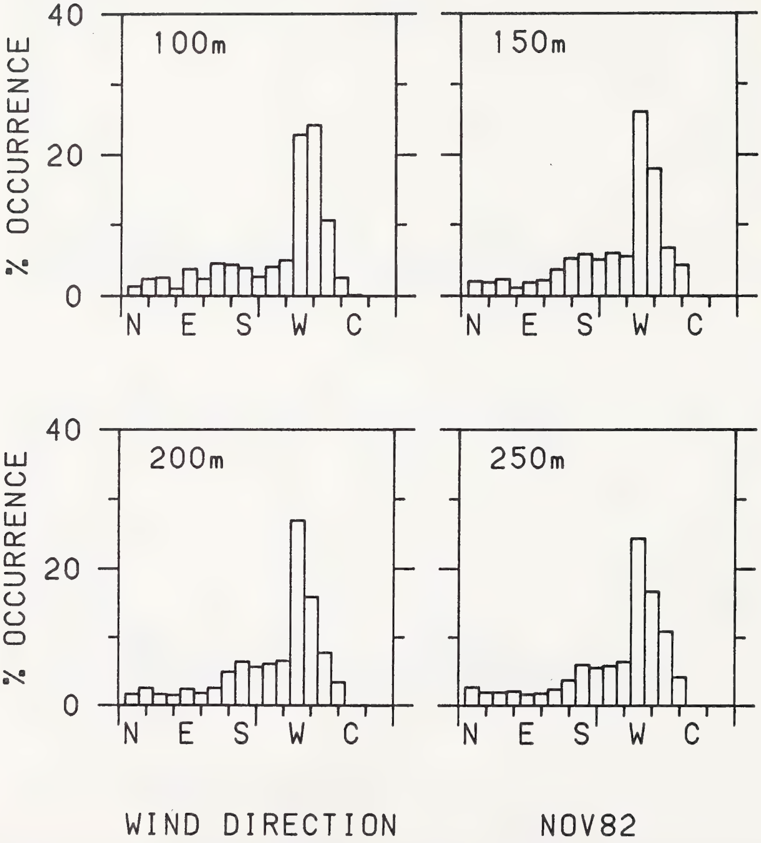

Figure 73. Distributions of Doppler wind directions for the month of November 1982.

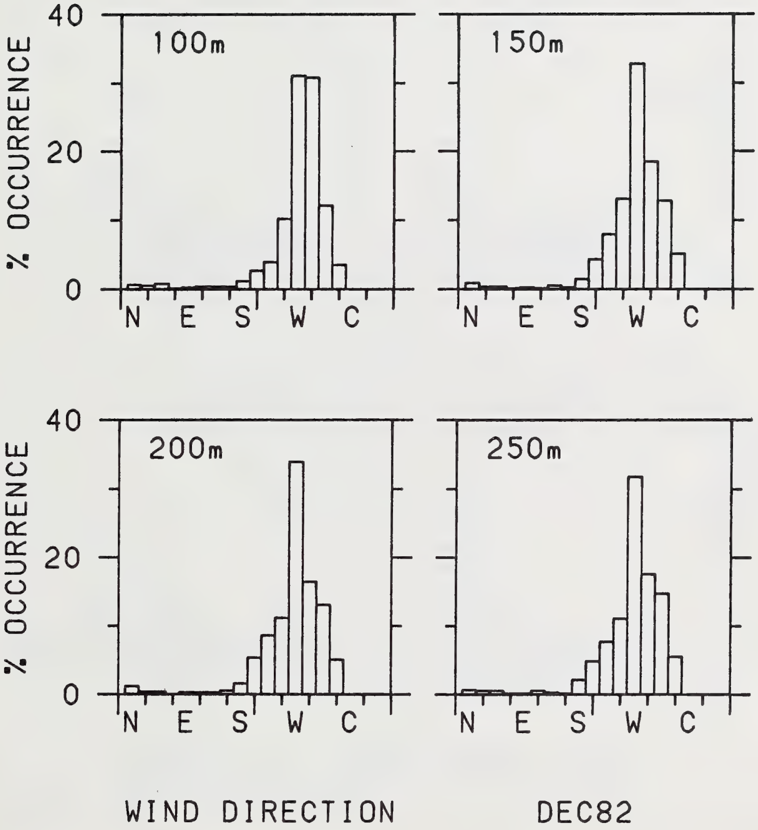

Figure 74. Distributions of Doppler wind directions for the month of December 1982.

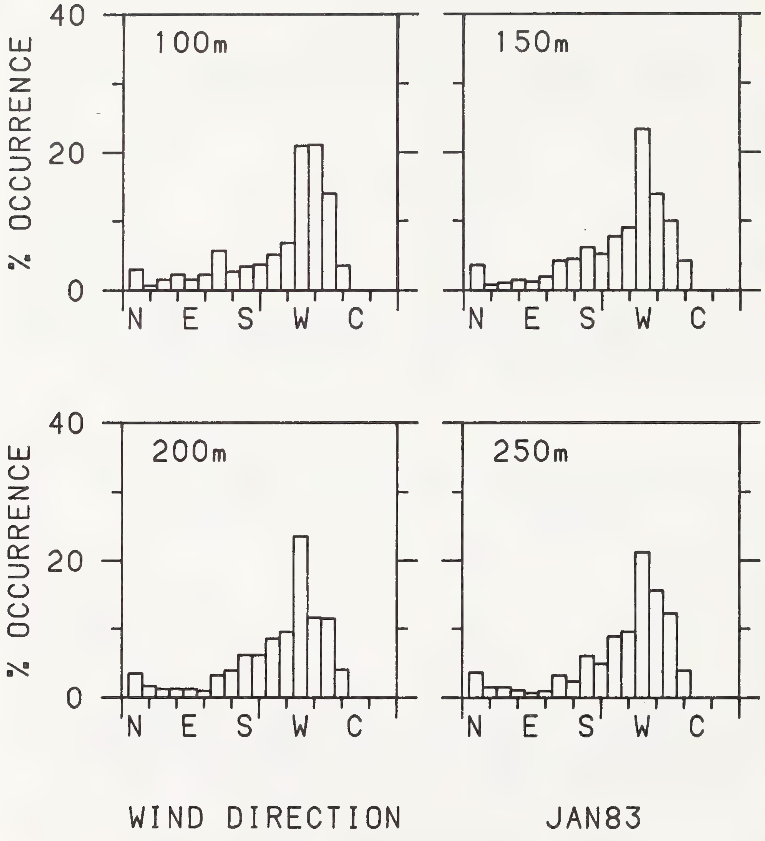

Figure 75. Distributions of Doppler wind directions for the month of January 1983.

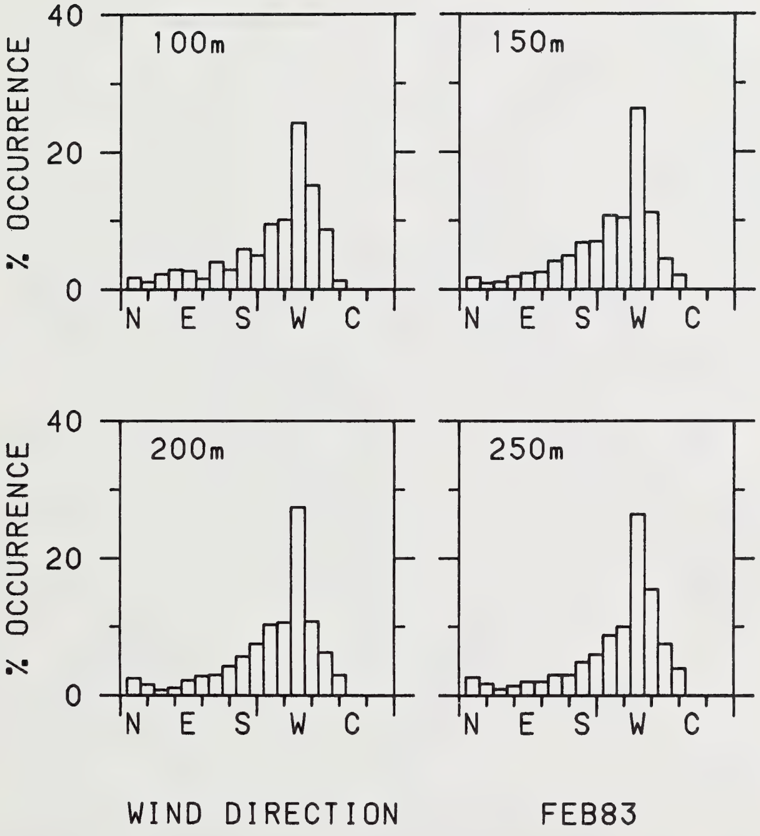

Figure 76. Distributions of Doppler wind directions for the month of February 1983.

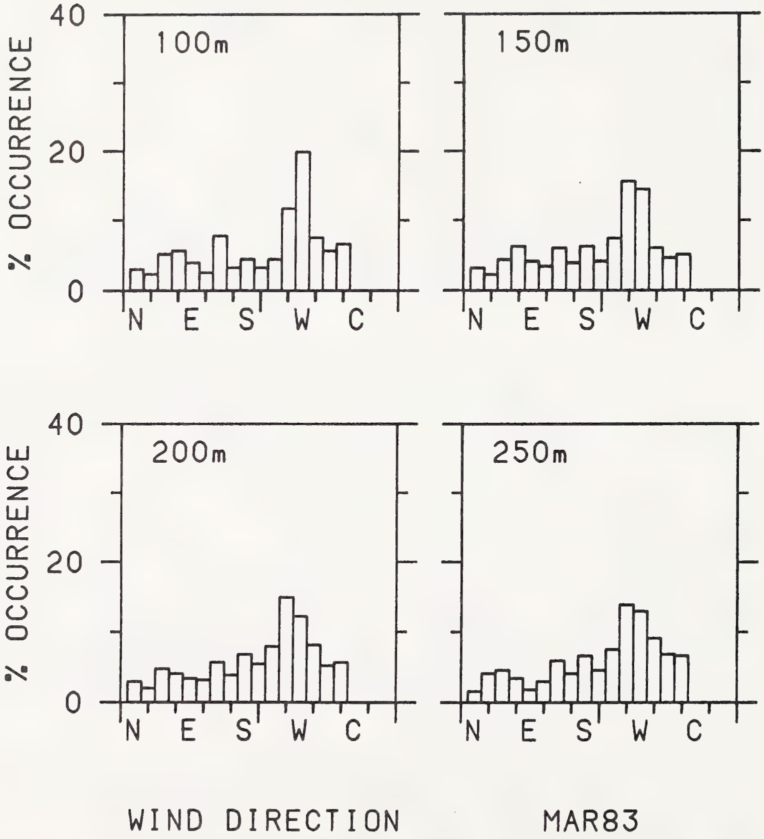

Figure 77. Distributions of Doppler wind directions for the month of March 1983.

8.5 CHINOOK EVENTS IDENTIFIED DURING WINTER MONTHS

The following table contains a list of Chinook events identified during the winter periods (November to March) of the study, together with brief descriptions of each event as it was observed by sodars and conventional surface instrumentation.

Table 12. Chinook events identified during winter months (all times MST).

Date	Sounder Derived Wind Data	Surface Wind and Temperature Data at CIA	Facsimile Records
1980-12-06/07	The upper level winds change to NW-SW at 1800 on the 6th; however, magnitude does not increase until 1200 on 7th when it increases significantly.	Temp. starts increasing at 2300 on 6th; strong westerly winds at 0100 on 8th.	Descending Chinook layer
1980-12-08	At 1400, wind speed decreases and becomes northerly (sudden change).	At 1400, temp. drops by 20°C. The winds become northerly but moderate to strong.	Rising layer
1980-12-09	At 0200 to 0300, wind speed starts increasing at all levels above 100 m and is westerly. However, at 1200 wind speed decreases and is from NE.	At 0500, temp. increases by 14°C and then decreases by 17°C at 1200. Moderate to strong northerly winds.	Descending layer is seen, which rises again
1980-12-10	Wind starts increasing at 0700 and becomes westerly; however, it varies until 1800 when it in-	Temp. starts increasing at 0900 and continues until 1200 when it has increased by	Descending Chinook layer

continued...

Table 12. Continued.

Date	Sounder Derived Wind Data	Surface Wind and Temperature Data at CIA	Facsimile Records
	creases significantly. The westerly flow continues until Dec. 15, with varying magnitude.	33°C. Winds pick up at 1800 on 10th and becomes W-SW.	
1980-12-13	Westerly flow with moderate magnitude at 0800 which increases significantly at 1700.	Temp. starts increasing gradually at 0800, rises by 18°C and then does not show even diurnal variation; winds also start increasing at 0800 and are westerly; at 1700 increase is very significant. These strong westerly winds continue for two days.	
1980-12-24	Winds start increasing after 1200 and become westerly; however, at 2300 again decrease	Temp. starts increasing at 0500; however, at 2100 temp. drops suddenly by 13°C and	Chinook layer

continued...

Table 12. Continued.

Date	Sounder Derived Wind Data	Surface Wind and Temperature Data at CIA	Facsimile Records
	sharply and change directions to S, SE, and E at various heights.	then remains constant for one day. The winds are light to moderate and northerly.	
1980-12-25/26	Around 1300 on 25th, the wind increases and changes direction to westerly. After midnight it decreases for a while but again picks up. The direction of flow remains westerly all through until 0200 on Dec. 31 except for short duration.	Temp. starts increasing at 2000 and remains considerably warmer until 0100 on Dec.31. The winds become westerly and strong at 2000 on 26th and continue for two days. The flow remains westerly until 31st but magnitude keeps on varying.	Chinook layer
1981-01-06	At 1200, wind speed increases and direction of flow becomes westerly. Although magnitude keeps on varying, the flow	Temp. increases at 1400 and remains warm during the night. Moderate to strong westerly winds at 1700 which	Chinook layers, but not well defined

continued...

Table 12. Continued.

Date	Sounder Derived Wind Data	Surface Wind and Temperature Data at CIA	Facsimile Records
	remains W-SW until 0300 Jan. 8.	continued through the night.	
1981-01-09	At 0600, wind increases and flow becomes westerly.	At 1100, temp. increases suddenly. The winds become strong and westerly at 1200.	Chinook layer, no structure from 1100 to 1630
1981-01-12	After 1200 flow was W-NW until 0200 on Jan. 14; however, the magnitude keeps on varying. (Note: no data before 1200.)	Sudden increase in temp. at 0500 by 6°C. Total rise in temp. has been 13°C over a few hours. Strong westerly winds at 0800 continuing for two hours.	
1981-01-17	Wind increases after 0800 and becomes westerly. The W-NW flow continues until Jan. 20 with varying magnitude.	Temp. starts to rise gradually at 0800 and increases by 24°C later. It maintains at the higher value for	Chinook layer, no structures 1300 to 1600

continued...

Table 12. Continued.

Date	Sounder Derived Wind Data	Surface Wind and Temperature Data at CIA	Facsimile Records
		about one day. Light to moderate westerly winds which become strong after 2000.	
1981-01-21	The wind starts increasing at 0200 and by 0600 it is strong and westerly. After 1100 it again decreases.	Temp. starts increasing at 0800 (16°C increase). At 1600 it decreases again; winds are strong and westerly during 1400 to 1600.	Chinook layer, no structure during 1100 to 1600
1981-01-24/25	Moderate to strong northerly winds.	Temp. remains constant near 0°C and winds are moderate to strong and from N.	
1981-02-12/13	Strong westerly wind after 1500 which decreases around 2300 and again picks up around 1600 on 13th and is strong westerly by 1900.	Temp. starts increasing steadily at 0300 on 13th and increases by 20°C at 1800; winds become strong and westerly at 2000.	Chinook layer reaching ground at 1700 at SPBK

continued...

Table 12. Continued.

Date	Sounder Derived Wind Data	Surface Wind and Temperature Data at CIA	Facsimile Records
1981-02-18	Strong westerly wind at 0900 which decreases after 2000.	Sudden increase in temp. by 8°C at 1000 and later on steady increase. Sudden increase in wind speed at 1000 and flow becomes westerly. It continues until 2000.	
1981-02-19	Strong westerly wind at 1400 which continues for almost three days. However, magnitude keeps on varying.	Sharp rise in temp of 6°C at 1300. The temp. remains considerably warmer for three days. However, diurnal variations are clearly superposed over it. The surface winds are also strong and westerly.	Chinook layer, not well defined
1981-03-02	Strong W winds at upper levels during 0100 to 1700.	Temp. increases at 0400 and moderately strong W winds during 0600 to 0900.	Chinook layer reaching ground at 0930

continued...

Table 12. Continued.

Date	Sounder Derived Wind Data	Surface Wind and Temperature Data at CIA	Facsimile Records
1981-03-13/15	At 2200 on 13th, the winds become WNW and strong, continuing up to 0400. Again on 15th at 1000 winds start increasing and change to westerly. After 2200 they become SW and light.	Temp. starts increasing at 0000 on 14th with winds moderately strong from WNW during 0100 to 0400. Again moderately strong W winds during 1500 to 1900 on 15th and temperature as high as 14.4°C.	Chinook layer
1981-03-27/29	Strong W winds during 1600 to 0400 on 27th, becoming light thereafter below 200 m. Again winds become strong westerly during 1400 to 0100 on 28th.	Strong westerly winds on 27th during 2100 to 0400, then decreasing and becoming southerly. Again strong westerly winds during 1600 0100 on 28th. Temp. remains quite warm during this period.	

continued...

Table 12. Continued.

Date	Sounder Derived Wind Data	Surface Wind and Temperature Data at CIA	Facsimile Records
1981-11-08	No data	0800 to 1500 temp. rises steadily. By 2000 temp. drops with easterly winds. Westerly onset at 2100 causes temp. to rise to a maximum at 1300 on Nov. 9, for a rise of 19.5°C.	
1981-11-14	No data	Warming begins 1100 but temp. falls at 0000 on the 15th, rising again until 0200 only to fall off at 0400, and finally rising to a maximum at 1300, for a temp. rise of 9.7°C. Westerlies begin at 0200.	

continued...

Table 12. Continued.

Date	Sounder Derived Wind Data	Surface Wind and Temperature Data at CIA	Facsimile Records
1981-11-19/20	No data	Warming from 2000 to 0200 on 20th, for a temp. rise of 8.5°C. Westerly onset at 2000 on 19th.	
1981-11-25	No data	Warming from 0700 to 1400 with temp. rise of 14.1°C. Westerly onset at 1300.	
1981-11-27	No data before 1600. At this time winds are WSW.	Warming from 0500 to 1400 for a temp. rise of 20°C. Westerly onset at 1900.	Descending layer
1981-12-01	No data	Warming from 0600 to 1300 for a temp. rise of 14.3°C. Westerlies begin at 0800.	

continued...

Table 12. Continued.

Date	Sounder Derived Wind Data	Surface Wind and Temperature Data at CIA	Facsimile Records
1981-12-07	200 m winds shift to W at 1100 from SSE. 100 m winds shift W at 1300 from WNW.	Warming from 1000 to 1500 for a temp. rise of 11°C. Westerly onset at 2000 after maximum temp. has occurred.	
1981-12-25	Data collection begins at 1300 on Dec. 24, with 250 m winds in westerly direction. 100 m westerlies develop at 0000 from SW direction.	Warming from 0800 to 1400 for a temp. rise of 11.3°C. Westerly onset at 0800 at beginning of warming trend.	Descending layer
1982-01-06	Westerlies develop at 250 m at 2100 on Jan. 5, from NW. 100 m winds shift to WNW at 0100 from NW and finally to strong westerlies at 1600.	Warming from 1000 to 1600 for a temp. rise of 18.3°C. Westerly onset at 1500.	Descending layer

continued...

Table 12. Continued.

Date	Sounder Derived Wind Data	Surface Wind and Temperature Data at CIA	Facsimile Records
1982-01-13	High altitude winds shift from S to W at 0500 while 100 m winds first shift to WNW at 0600 and finally to W at 0900.	Warming from 0900 to 1300 for temp. rise of 15.8°C. Westerly onset at 0900 at beginning of warming trend.	Descending layer
1982-01-24	Winds alternate between WNW and W beginning at 0800. At 1600 winds below 150 m align to W while upper winds continue WNW to W.	From 0500 to 1200, the temperature increases steadily. From 1300 to 1500 winds shift NE and temp. drops. At 1600 wind aligns to SSW and temp. rises. At 2000 westerly onset brings temp. to maximum at 0200 on the 25th.	Descending layer

continued...

Table 12. Continued.

Date	Sounder Derived Wind Data	Surface Wind and Temperature Data at CIA	Facsimile Records
1982-02-15	No data available after 0400. Winds steady SSE.	Warming begins at 1300. Temperature drops at 2100, 0200, and 0500 on the 16th. Temp. reaches a maximum at 1700 for a rise of 13.2°C. Westerlies begin at 1300 on 16th.	Descending layer
1982-02-18	Winds constantly shift from WSW to WNW.	Warming from 1100 to 1700 for a temp. rise of 14.2°C. Westerlies begin at 0000 on Feb. 19 after warming peak.	
1982-03-08	Wind shift to W at 1900 from SSW.	Warming from 0900 to 0200 on Mar. 09 for a rise of 27.2°C. Westerlies begin at 2200.	

continued...

Table 12. Continued.

Date	Sounder Derived Wind Data	Surface Wind and Temperature Data at CIA	Facsimile Records
1982-03-12	No data.	Warming from 0700 to 1500 for temp. rise of 10.9°C. Westerly onset on 0700 at beginning of warming phase.	
1982-03-13	No data before 1000. At this time winds are WNW.	Warming from 0900 to 1500 for a temp. rise of 8.5°C. Westerlies begin at 0800.	
1982-11-23	At 0000 winds shift from NW to W. At 0900 upper winds increase, changing to ESE for two hours. At 1600, winds	Warming begins 0800, increasing by 6°C by 1000 at which time WSW winds (13 km/h) being. The temp. continues	Descending layer

continued...

Table 12. Continued.

Date	Sounder Derived Wind Data	Surface Wind and Temperature Data at CIA	Facsimile Records
	increase and remain westerly. At 0500 on Nov. 24, the direction shifts NW and magnitude drops.	to increase by a further 9°C to a total rise of 15°C. By 2100, winds have shifted to the W at 28 km/h.	
1982-11-26	At 1800 on the Nov. 25, winds shift from SW, gradually increasing and becoming westerly by 2300. At 0600 on the 26th, winds shift to E for one hour, returning to strong westerlies. At 1200 westerlies end, shifting to an easterly direction.	Warming begins at 0700 until 1900 with a temp. rise of 20°C. Strong westerlies begin at 1800.	Descending layer

continued...

Table 12. Continued.

Date	Sounder Derived Wind Data	Surface Wind and Temperature Data at CIA	Facsimile Records
1982-11-28	Weak westerlies begin at 2000 on Nov.27, gradually strengthening, ending at 1200 on 28th.	Warming begins at 1000. By 1400 temperatures have risen 13°C. Westerlies occur at 1400, gradually increasing.	
1982-12-03	At 1500, upper winds become westerly (formerly SSW). Lower winds remain light and variable in direction. At 0400 on 4th, winds become strong and northerly.	Warming from 1000 to 1700 with 16°C rise in temperature. Strong WSW winds develop at 1700.	Two descending layers
1982-12-08	Westerlies develop at 0300. By 0700 on 9th, winds shift to NW.	Warming from 0400 to 1800 with 20°C rise in temperature. Westerlies begin at 1800.	Descending layer

continued...

Table 12. Continued.

Date	Sounder Derived Wind Data	Surface Wind and Temperature Data at CIA	Facsimile Records
1982-12-19	Westerlies develop at 0200. Lower winds shift to NNW 0600 to 0900, and E 1300 to 1700. Starting 0500 on 20th, winds begin to shift to NNW.	Warming from 0900 to 1300; 10°C rise in temperature. Westerlies begin at 1200.	
1982-12-22	Upper winds become westerly at 1000 (formerly SSW), with an increase in magnitude at 1500. 0300 to 0700 on Dec. 23, winds shift to NW.	Warming from 1400 to 2000 with 7°C rise in temperature.	Descending layer
1982-12-24	Westerlies develop at 2000. From 0300 to 0600 winds are light and variable. By 1400 on Dec. 25, winds shift to light SSE.	Warming 0800 to 1800 with 15°C temperature rise. Strong westerlies at 1800.	

continued...

Table 12. Continued.

Date	Sounder Derived Wind Data	Surface Wind and Temperature Data at CIA	Facsimile Records
1983-01-02	Westerlies develop at 0000 (formerly SW). Winds shift northerly at 1300.	Warming 0400 to 1400 with 19°C temperature rise. Weak westerlies develop at 0900.	Weak descending layers
1983-01-11	Strong westerlies develop at higher altitudes at 0900. By 1100 all winds are westerly. By 1900 winds are SSW.	Warming 0900 to 1400 with 29°C rise in temperature. Strong westerlies begin 1500.	Descending Chinook layer
1983-02-12	Westerlies form at 1600. At 2000 on Feb. 13, winds drop and become variable in direction.	Warming 0900 to 1200 with 12°C temperature rise. Westerlies begin at 1200.	
1983-02-20	Westerlies develop 0700 (formerly SW). By 1900 westerlies begin to drop off and gradually shift N.	Warming 0700 to 1600 with 14°C temperature rise. Westerlies begin at 1600.	

continued...

Table 12. Concluded.

Date	Sounder Derived Wind Data	Surface Wind and Temperature Data at CIA	Facsimile records
1983-03-09	Westerlies develop 0700 (formerly S). At 2200 lower winds shift to NE. At 0500 on Mar. 10 higher altitude winds shift SSW.	Warming 0700 to 1600 with 19°C rise in temperature. WSW winds begin at 1600, continuing until 2300.	Descending layer with oscillations